PB85-120970

Granular Activated Carbon for Removing Nontrihalomethane Organics from Drinking Water

(U.S.) Municipal Environmental Research Lab.
Cincinnati, OH

Nov 84

U.S. Department of Commerce
National Technical Information Service
NTIS

PB85-120970

EPA-600/2-84-165
November 1984

GRANULAR ACTIVATED CARBON FOR REMOVING NONTRIHALOMETHANE ORGANICS FROM DRINKING WATER

by

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CINCINNATI, OH 45268

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SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-84-165	2.	3. RECIPIENT'S ACCESSION NO. PB85 120970
4. TITLE AND SUBTITLE GRANULAR ACTIVATED CARBON FOR REMOVING NONTRIHALOMETHANE ORGANICS FROM DRINKING WATER		5. REPORT DATE November 1984
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Benjamin W. Lykins Jr., Edwin E. Geldreich, Jeffrey Q. Adams, John C. Ireland, and Robert M. Clark		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Municipal Environmental Research Laboratory Office of Research and Development U. S. Environmental Protection Agency Cincinnati, OH 45268		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. Inhouse
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin., OH Office of Research and Development U. S. Environmental Protection Agency Cincinnati, OH 45268		13. TYPE OF REPORT AND PERIOD COVERED Summary Report 1976 - 1984
		14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

B. W. Lykins, Jr., Project Officer (513) 684-7460

16. ABSTRACT

Several large field scale research projects were initiated by the U. S. EPA Drinking Water Research Division, MERL, Cincinnati, OH to evaluate the performance of GAC under varying operating conditions and different source water. Most of this research has been completed at nine locations (Cincinnati, OH; Manchester, NH; Jefferson Parish, LA; Evansville, IN; Miami, FL; Huntington, WV; Beaver Falls, PA; Passaic, NJ; and Thornton, CO).

Various carbons produced for organics removal were evaluated at the nine locations. Over 150 specific organics were detected at these locations. In addition to these specific organics, surrogate parameters such as total organic carbon and total organic halide were used in many cases to determine GAC performance. Most of these compounds were removed by GAC. Also, microbiological data was evaluated.

Actual cost data associated with the construction and operation of full scale research facilities were summarized. In addition, cost estimates for various GAC treatment scenarios were developed to examine the effect of economies of scale and cost tradeoffs between alternative GAC treatment systems.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 268
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a most vital communications link between the researcher and the user community.

Granular activated carbon has been in use for various reasons for many years. Although its adsorptive ability for removal of specific organics is well-established, only recently have drinking water utilities considered granular activated carbon a viable treatment alternative for removal of these organics. Sufficient information is available from several EPA research projects to provide treatment performance, bacteriologic quality, and economic impact of granular activated carbon use for treating surface waters.

Franics T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

Granular activated carbon (GAC) has been in use for many years to remove taste and odors in drinking water. Within the past ten years, some utilities have seriously considered the use of GAC for removal of trace organics from their drinking water. With more sophisticated instrumentation rapidly becoming available that is affordable and useable by utilities, more organics at trace concentrations are being detected. Utility managers as well as the general public are becoming more concerned about the health effects of ingesting these trace concentrations of various organics over many years.

To provide adsorption efficiency data, considering the mix of compounds in drinking water sources and competition for available adsorption sites, GAC was investigated under actual operating conditions. Several large field scale research projects were initiated by the U.S. EPA Drinking Water Research Division, Cincinnati, Ohio to evaluate the performance of GAC under varying operating conditions and different source water. Most of the GAC research effort has been completed at nine locations (Cincinnati, OH; Manchester, NH; Jefferson Parish, LA; Evansville, IN; Miami, FL; Huntington, WV; Beaver Falls, PA; Passaic, NJ; and Thornton, CO).

Various carbons produced for organics removal were evaluated at the nine locations. Over 150 specific organics were detected at these locations. In addition to these specific organics, surrogate parameters such as total organic carbon (TOC) and total organic halide (TOX) were used in many cases to determine GAC performance. Most of these compounds were removed by GAC. Low molecular weight compounds such as 1,2-dichloroethane were continuously removed for periods up to 100 days. Higher molecular weight compounds such as the chlorinated herbicide atrazine were removed through 180 days of operation.

At three locations (Cincinnati, Jefferson Parish, and Thornton) both the post-sand filter adsorber and the sand replacement adsorber were evaluated. The performance of these two systems were found to be comparable. Also, pilot systems at these sites generally predicted the performance of their full-scale counterparts.

After exhaustion, GAC was reactivated on-site at three locations (Cincinnati, Manchester, and Passaic) and off-site at Evansville. Reactivation systems included a 227 kg (500 lb) per hour fluidized bed furnace and a 45.4 kg (100 lb) per hour infrared furnace. Several properties were evaluated to ensure that proper reactivation had occurred. The performance of subsequently reactivated GAC was comparable to the virgin carbon at Cincinnati as determined by the TOC loading. The same general trend was seen for Evansville through two reactivations. At Manchester, the subsequently reactivated

carbon performed better than the virgin carbon. Reactivation performance properties (iodine number and apparent density) showed that the reactivated carbon was restored to essentially virgin conditions at Passaic.

From an economic standpoint, the most important GAC operational criteria to consider is carbon losses resulting from reactivation and transport. Total average losses (by volume) for the GAC adsorbers ranged from 8 percent for the infrared furnace to 15 percent for the fluidized bed furnace.

Actual cost data associated with the construction and operation of full-scale research facilities at Cincinnati and Manchester have been summarized. In addition, cost estimates for various GAC treatment scenarios have been developed to examine the effect of economies of scale and cost tradeoffs among alternative GAC treatment systems. Concrete gravity GAC contactor systems appear to exhibit lower total water production costs (adsorption plus reactivation) than steel pressure GAC contactor systems given the same water quality goal.

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ACKNOWLEDGMENTS

Completion of a comprehensive document such as this one incorporating data from several research studies requires support from several individuals. A major effort in producing the graphics was supplied by Sue Campbell and staff of the Computer Science Corporation (Diane Westendorf, Jeff Finkeldey, and Sue Schwartz). Review comments were provided by Gordon G. Robeck, Robert M. Clark, Alan A. Stevens, Walter A. Feige, O. Thomas Love, Jr., Richard Miltner, J. Keith Carswell, Thomas J. Sorg, and Gary S. Logsdon. The tenacity, patience, and understanding needed to type and re-type this document was provided by Patricia Pierson, Maura Lilly, Elizabeth Creamer, and Betty Wilkinson.

GRANULAR ACTIVATED CARBON FOR REMOVING NONTRIHALOMETHANE ORGANICS FROM DRINKING WATER

SECTION I

INTRODUCTION

Granular activated carbon (GAC) has long been considered a broad spectrum adsorbent for removal of synthetic organics and naturally occurring taste and odor compounds. The efficacy of this adsorbent, considering the mix of compounds in the source of drinking water and the competition for available adsorption sites, needed to be investigated in the field under actual operating conditions. Given this need, several large field scale research projects were initiated by the U.S. Environmental Protection Agency, Drinking Water Research Division, Cincinnati, Ohio to investigate the performance of GAC under varying operating conditions and with different source waters.

Sampling schemes were developed and analytical methodologies utilized to screen for various organics, surrogates for organics, microbiological and general operating parameters. Several thousand pieces of data have been generated from this effort and stored in the U.S. Environmental Protection Agency North Carolina Computing Center at Research Triangle Park, North Carolina. These data will be utilized to report on the removal or reduction of specific organics and total organic carbon (TOC). The trihalomethanes will not be discussed because they have been addressed extensively in another document.(1)

In addition, other areas covered in this report include:

- positive and negative aspects of GAC reactivation.
- microbiological ramifications resulting from GAC use and control measures required.
- cost of GAC treatment including on-site and off-site reactivation, GAC replacement, and regional reactivation.

SECTION II

WATER UTILITIES PARTICIPATING IN GAC RESEARCH

Nine utilities have participated in cooperative GAC research efforts. Listed below are the locations of these utilities and some of the objectives established for each.

- Cincinnati, Ohio

  1. Determine if the use of granular activated carbon utilizing either deep bed contactors or conventional depth gravity filters with on-site GAC reactivation is feasible for removing specific trace organics from Ohio River water while treating it for human consumption. Bench scale pilot columns were compared to full scale deep bed, post filtration activated carbon contactors (adsorbers) and to conventional depth sand replacement carbon beds (filter adsorbers).

  2. Evaluate on-site fluidized-bed GAC reactivation for cost of operation and reactivation performance.

  3. Develop plant design and operating parameters for full-scale plant conversion to GAC treatment.

- Manchester, New Hampshire

  1. Evaluate the cost and performance of a GAC reactivation system utilizing fluid bed principles.

  2. Evaluate the cost and performance of a semiautomatic system for hydraulically transporting GAC to and from its point of reactivation.

  3. Determine the adsorptive effectiveness of both virgin and reactivated GAC for removing TOC from Manchester drinking water.

- Jefferson Parish, Louisiana (JP-1)*

  1. Provide data on the efficiency of GAC bed adsorption for a wide range of organic chemicals. This included data on the frequency at which hydrocarbons enter the process stream from the raw water source. Also, removal of organic species by various treatment units or processes were investigated such as: lime softening, polyelectrolyte treatment, addition of potassium permanganate, flocculation, filtration, post-filtration adsorption, and combined filtration adsorption (filter adsorber).

  2. Investigate certain non-specific parameters such as TOC for use as surrogate monitoring parameters for GAC applications.

  3. Compare the relative efficiency of post-filtration adsorption vs. combined filtration adsorption.

  4. Determine the reliability of using pilot column simulators for predicting full-scale GAC performance.

- Evansville, Indiana

  1. Develop a water treatment process using chlorine dioxide as a disinfectant to evaluate the resultant production of any organic compounds and their removal by GAC. Also, determine the effectiveness of virgin and subsequently reactivated GAC for removal of any organics whether present in the source water or formed during treatment.

- Miami, Florida

  1. Conduct bench-scale study on the effectiveness of two adsorbent resins and one type of GAC in removing various organic compounds from raw and treated drinking water.

- Ohio River Sanitation Commision (ORSANCO) Huntington, West Virginia and Beaver Falls, Pennsylvania

  1. Investigate and evaluate full-scale GAC treatment for control of organic compounds.

- Passaic Valley, Little Falls, New Jersey

  1. Evaluate the efficiency of three types of GAC before and after infrared reactivation.

---

*Two GAC research projects were started at Jefferson Parish, Louisiana. One is currently on-going so that only the first project (JP-1) will be discussed in this report.

° Thornton, Colorado

1. Evaluate the effectiveness of GAC after coagulation/settling (filter adsorber) and after sand filtration (adsorber).

SECTION III

DESCRIPTION OF FULL-SCALE PLANTS AND PILOT SYSTEMS

Each full-scale facility involved in the GAC research effort basically utilized the same treatment scheme: pre-disinfection, coagulation/flocculation, settling, filtration, and post-disinfection. Minor variations to this treatment scheme were practiced by a few utilities. A general description of each full-scale and pilot plant operation is presented below as background information in relationship to the performance data that will be presented later.

A. Cincinnati, Ohio(2)

Full-Scale Treatment Plant (Figure 1)

The primary source water for the Cincinnati Water Works is the Ohio River. Raw water is pumped into large presettling basins having a combined capacity of 1.4 million cu m (372 million gallons) and a retention time of 2 to 3 days. Alum at an average dose of 17 milligrams per liter (mg/L) is added to the raw water to aid settling. Occasionally, powdered activated carbon (PAC) is added to the raw water as a sunlight screen to deter algae growth in the presettling basins (taste and odor control) and to lessen the effect of a chemical spill.

From the presettling basins, water flows through two parallel water turbine-powered generators that serve as a velocity breaker. The turbine discharge flow is split into two hydraulic jumps, thereby providing rapid mixing of chemicals. Average chemical addition at this point includes lime (17 mg/L), ferric sulfate (8.6 mg/L for high turbidity and 3.4 mg/L for filter conditioning during periods of low turbidity), fluoride (to produce a plant effluent concentration of 0.9 mg/L), and chlorine (typical plant effluent concentration was 1.8 mg/L free chlorine).

The hydraulic jumps direct water to two parallel basins for flocculation followed by clarification. Each basin has a capacity of 49,215 cu m (13 million gallons). Two flumes direct water to 47 rapid sand gravity filters (gradations of gravel and sand), each having an effective area of 130 sq. m (1400 sq ft) with a hydraulic loading of 6.0 m/hr (2.5 gpm/sq ft or 5 mgd). Finished water is directed to either of two underground clearwells before distribution. Total design flow of the plant is 10.3 m^3/sec (235 mgd) with a typical demand of about 5.7 m^3/ sec (130 mgd).

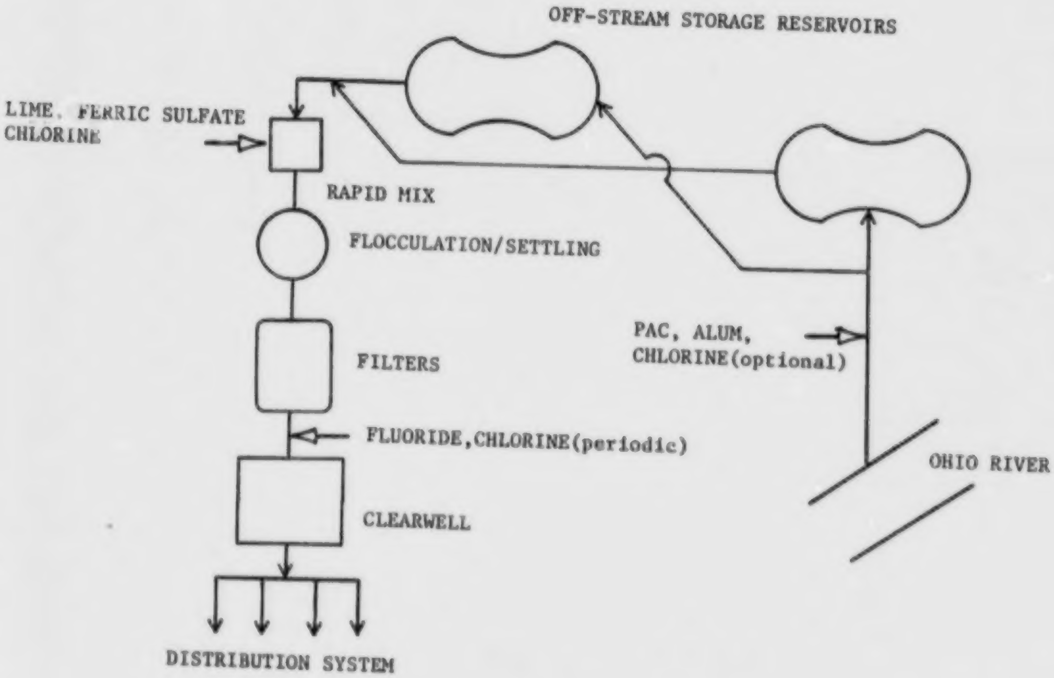
OFF-STREAM STORAGE RESERVOIRS
LIME. FERRIC SULFATE
CHLORINE
RAPID MIX
FLOCCULATION/SETTLING
FILTERS
FLUORIDE,CHLORINE(periodic)
CLEARWELL
DISTRIBUTION SYSTEM
PAC, ALUM,
CHLORINE(optional)
OHIO RIVER

FIGURE 1. SCHEMATIC OF CINCINNATI, OHIO WATERWORKS

Modification of Existing Sand Filters

During the GAC study, four of the water treatment plant's 47 sand filters were converted to GAC filters. One other sand filter was used for storage of make-up GAC. Because the "Ten State Standards"(3) require a minimum of 30.5 cm (12 in) of filter sand for turbidity removal, only 45.7 cm (18 in) of one filters 76.2 cm (30 in) of sand was removed and replaced with Westvaco 12 x 40 WVG® GAC.

With the concurrence of the Ohio EPA, all of the sand (76.2 cm, 30 in) in three other filters was replaced with GAC. Westvaco 20 x 50 WVW® GAC was used in one of these filters to coincide with the effective size (0.45 to 0.55 mm) of the sand. This filter and the one with 45.7 cm (18 in) of GAC was used as post sand filtration adsorbers. The other two filters contained 76.2 cm (30 in) of Westvaco 12 x 40 WVG® GAC and were used as filter adsorbers, receiving water before sand filtration (after coagulation/settling). Average empty bed contact times (EBCT) for all of the modified filters were around 7.5 minutes.

GAC Contactors

The performance of the previously described conventional depth (76.2 cm, 30 in) gravity filters were compared to deep bed contactors (4.6 m, 5 ft). Four contactor tanks were utilized for this comparison. Each contactor was of cylindrical shell construction of 9.55 mm (3/8 in) thick carbon steel plate designed to the following specifications:

Diameter	3.4 m (11 ft)
Vertical Sidewall Height	6.7 m (22 ft)
GAC Depth	4.6 m (15 ft)
Design Capacity	0.04 cu m/sec (1.0 mgd)
Hydraulic Loading	17.8 m/hr (7.4 gpm/sq ft)
Contact Time	15.3 min.
Design Pressure	517.1 kPa (75 psig)
Test Pressure	620.5 kPa (90 psig)
Backwash Hydraulic Loading	24 m/hr (10 gpm/sq ft)

The GAC used in each contactor was 12 x 40 WVG®.

GAC Pilot Columns

Bench scale glass columns 7.6 cm (3 in) in diameter were used to simulate the sand replacement filter beds. Two columns 1.4 m (54 in) in height and containing 76.2 cm (30 in) of 12 x 40 WVG® GAC were utilized. In addition, pilot columns were used for performance comparision to the deep bed contactors. One set of four columns in series contained ICI Hydrodarco® 1030 GAC. Each of these columns was 10.2 cm (4 in) in diameter and 1.8 m (6 ft) in height. The first column in the series had 0.9 m (3 ft) of GAC and each of three successive columns had 1.2 m (4 ft) of GAC for a total GAC depth of 4.6 m (15 ft).

Another series of columns was comprised of four 1.5 m (5 ft) sections 10.2 cm (4 in) in diameter. These columns contained WV-G® 12 x 40 GAC. The first column consisted of 0.9 m (3 ft) of GAC while each of the three succeeding columns contained 1.2 m (4 ft) of GAC giving an aggregate GAC depth of 4.6 m (15 ft).

B. Manchester, New Hampshire(4)

Full-Scale Treatment Plant (Figure 2)

Lake Massabesic serves as the principal water source for the City of Manchester. This lake supply is of natural origin having a watershed of 44 square miles. Water treatment is accomplished in a 1.8 m^3/sec (40 mgd) capacity facility.

The treatment process consisted of five sequential unit processes beginning with flash mixing followed by flocculation, sedimentation, sand filtration, and GAC adsorption. Water was delivered to the flash mix basin by a low lift intake station located on the shore of Lake Massabesic. In the flash mix basin, alum and sodium aluminate were added for coagulation, pH adjustment, and alkalinity control at dosage levels averaging about 12 mg/L and 8 mg/L, respectively. Water flowed through a common distribution channel to four covered flocculation tanks. Flocculation detention time was about 1.3 hours at an average day finished water flow of 0.6 m^3/sec (13 mgd).

Water from the flocculation tanks passed through a row of baffles to four covered sedimentation basins. Sedimentation detention time averaged about five hours at the average flow. Following sedimentation, water flowed over a series of serpentine-type weirs into a common effluent channel where it was directed into the filter room. Filtration was accomplished by four 27.9 cm (11 in) deep rapid sand filters (effective size 0.60 to 0.65 mm) followed by adsorption on four GAC filters containing 1.2 m (48 in) deep beds of Westvaco WVW® 8 x 30 carbon. Both the sand and GAC filters were 4.9 m (16 ft) in width by 33.5 m (110 ft) in length. All of the filters contained compartmented filter cells one foot in diameter. The sand filters were equipped with automatic backwash (ABW) filter carriages that traveled the length of the filter individually backwashing the cells without taking the filter out of service. Average hydraulic loading was 3.4 m/hr (1.4 gpm/sq ft) and the EBCT for each GAC filter was about 22 minutes.

Disinfection was accomplished by pre and post chlorination. Pre chlorine was added just before sand filtration at an average dose of 1 mg/L. Post chlorine was added at the clearwell in the range of 2.0 to 3.0 mg/L to produce an average distribution free chlorine residual of 0.5 mg/L.

Full-Scale GAC Evaluation

In order to evaluate GAC during full-scale application, one of the four GAC filters normally used for taste and odor control was utilized as a test filter. At the beginning of the study, one half of the filter con-

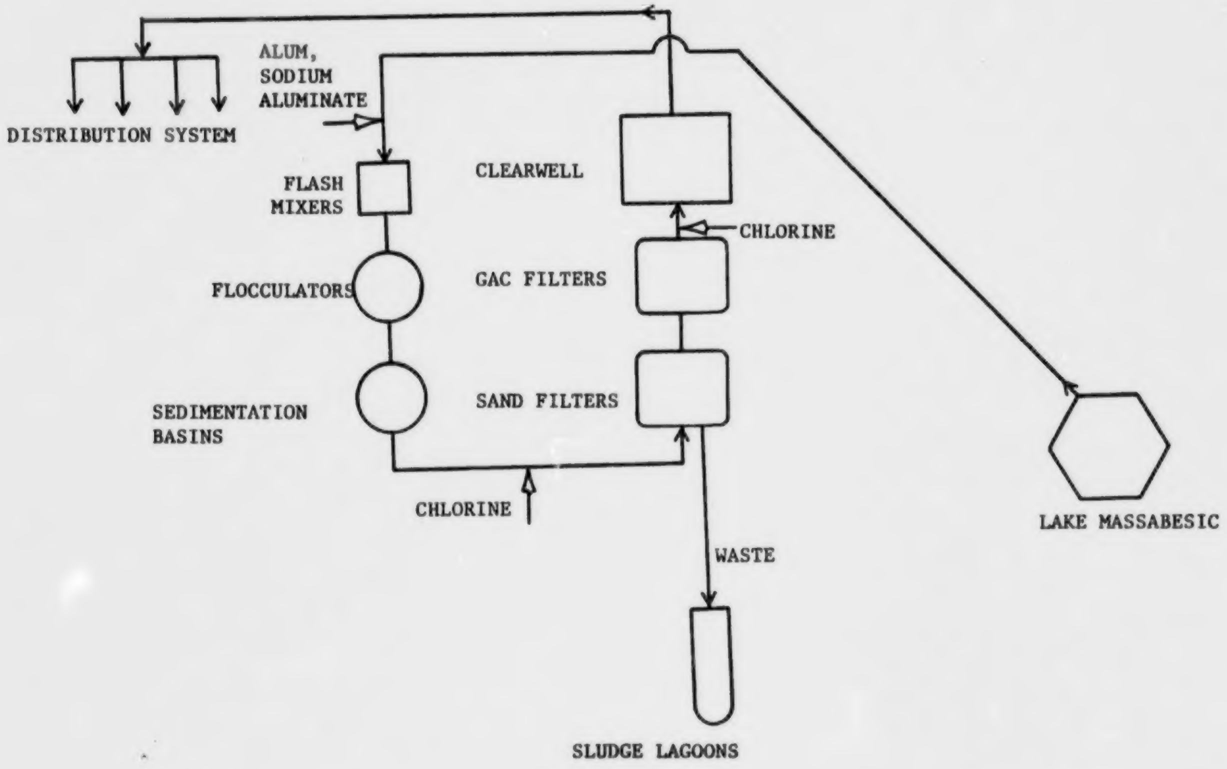
DISTRIBUTION SYSTEM
ALUM,
SODIUM
ALUMINATE
FLASH
MIXERS
FLOCCULATORS
SEDIMENTATION
BASINS
CLEARWELL
CHLORINE
GAC FILTERS
SAND FILTERS
CHLORINE
WASTE
SLUDGE LAGOONS
LAKE MASSABESIC

FIGURE 2. SITE PLAN – MANCHESTER, N.H. WATER TREATMENT PLANT

tained virgin WVW® 8 x 30 mesh GAC and the other half once reactivated GAC (5-year old service carbon reactivated at the beginning of the study). A complete separation of the GAC was possible because the GAC filters contained 110 cells spaced at 30 cm (12 in) centers.

C. Jefferson Parish, Louisiana(5)

Full-Scale Treatment Plant (Figure 3)

The conventional treatment plant at Jefferson Parish pumped raw source water from the Mississippi River. Total design flow of this plant was 3.1 m^3/sec (70 mgd) utilizing four separate smaller treatment plants with a demand of about 2.4 m^3/sec (55 mgd). Only one of the smaller plants within the treatment complex was used for this research effort at a design flow of 0.4 m^3/sec (10 mgd).

Potassium permanganate (0.5 - 1.0 mg/L) was added for taste and odor control as the first treatment step. A cationic polyelectrolyte (diallyldimethyl diammonium chloride (0.5 - 8.0 mg/L) was then added as the primary coagulant. Lime (7 - 10 mg/L) was continuously fed for pH adjustment to 8.0 - 8.3. After the precipitators, chlorine and ammonia were added in a ratio of 3:1 for chloramine disinfection before sand filtration. Monochloramine concentrations prior to the adsorbers and filter adsorbers ranged from 1.4 - 1.7 mg/L.

Although the above presents the general treatment scheme, some deviations did occur. On occasion, ferric chloride was added as a coagulant aid in an attempt to reduce the high cost of the polyelectrolyte. The addition of lime was discontinued at one point and sodium hexametaphosphate added for corrosion control in the sand filter system.

Two sand filters were converted to granular activated carbon beds for evaluation. One was designated filter adsorber because it served a dual purpose of removing filterable turbidity and adsorption of dissolved organic compounds. This filter received clarified chloraminated water. Media for the filter adsorber consisted of a 15.2 cm (6 in) layer of sand covered by 61 cm (24 in) of GAC in two modes of operation (I and IIA). During the other modes, the sand layer was removed so that the filter adsorber contained 76.2 cm (30 in) of GAC. For modes I, IIA, and IIB, the GAC was Westvaco WVG® 12 x 40 and for mode III Calgon Filtersorb 400®.

The second filter was utilized as an adsorber for post-sand filter adsorption. This filter consisted of 76.2 cm (30 in) of the same type of GAC used in the filter adsorber. The average hydraulic loading for these filters was 2.2 m/hr (0.9 gpm/ft^2) with corresponding EBCTs of 17.5 and 20.4 min., respectively, for the filter adsorber and adsorber.

Pilot Columns (Figure 3)

Two GAC pilot columns were operated under the same conditions and in parallel with their full-scale counterparts, filter adsorber and adsorber.

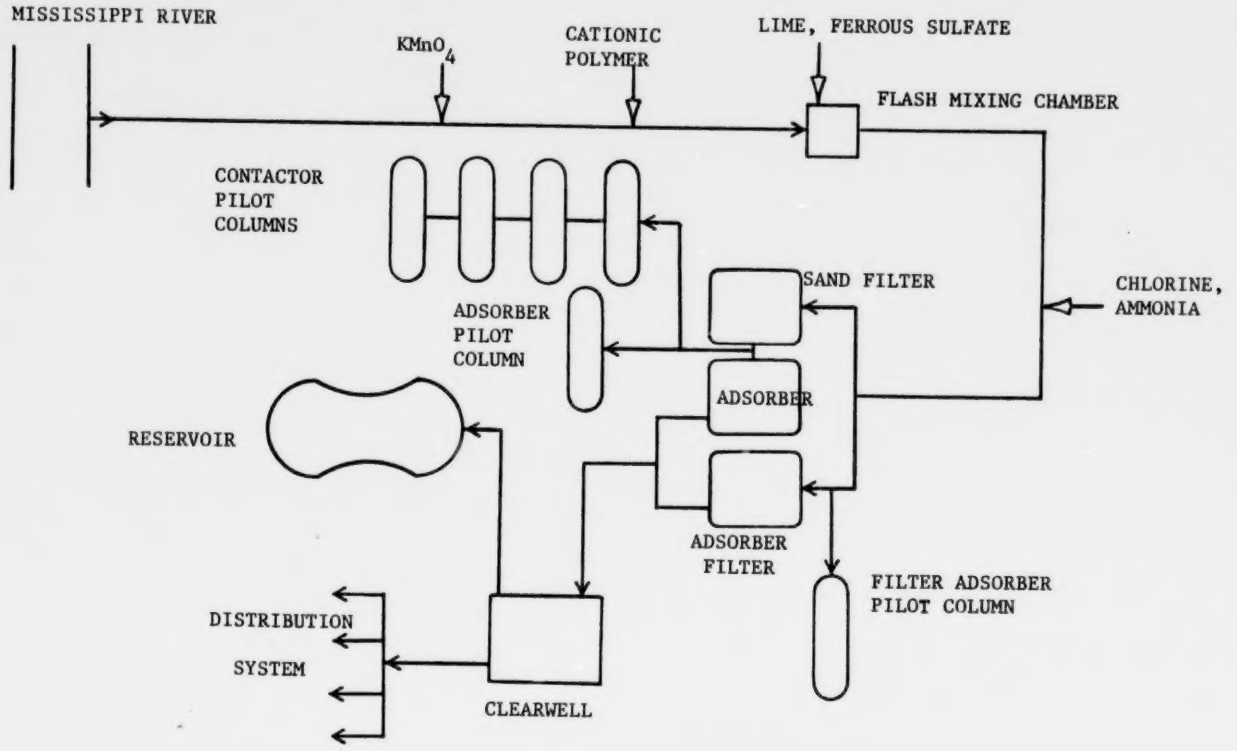
MISSISSIPPI RIVER
KMnO4
CATIONIC POLYMER
LIME, FERROUS SULFATE
FLASH MIXING CHAMBER
CONTACTOR PILOT COLUMNS
SAND FILTER
CHLORINE, AMMONIA
ADSORBER PILOT COLUMN
ADSORBER
RESERVOIR
ADSORBER FILTER
FILTER ADSORBER PILOT COLUMN
DISTRIBUTION SYSTEM
CLEARWELL

FIGURE 3. FULL-SCALE FILTER AND PILOT COLUMN FLOW CHART FOR JEFFERSON PARISH, LA.

These pilot columns were given the designations of adsorber simulator and filter adsorber simulator. Each column received influent water from the same sources and at the same relative hydraulic loadings as the full-scale units.

The pilot column simulators were constructed of glass 7.6 cm (3 in) in diameter and 1.5 meters (5 ft) in height and contained 76.2 cm (30 in) of GAC on top of 15.2 cm (6 in) of gravel support. Also, four other GAC pilot columns were operated in series at a flow rate of 0.76 L/min (0.2 gal/min) to simulate the effects of 10, 20, 30, and 40 minutes of EBCT on post-filtration contactors. These glass columns were 10.2 cm (4 in) in diameter, 1.8 meters (6 ft) in height and contained 91.4 cm. (36 in) of GAC on top of 15.2 cm (6 in) gravel support. The influent water for these pilot post-filtration contactors was the same as that for the adsorber filter and adorber simulator column.

D. Evansville, Indiana(6)

Full-Scale Treatment Plant (Figure 4)

The Evansville Waterworks Filtration Plant uses the Ohio River as source water with intakes about 1.6 Km (one mile) upstream from the city of Evansville. This plant consists of two separate treatment systems (North and South Plants) with each having a hydraulic capacity of approximately 1.3 m^3/sec (30 MGD). The South Plant was used as a control while evaluating the performance of an on-site pilot plant.

The South Plant consisted of two primary settling basins, two secondary settling basins, and eight rapid sand filters. Each primary settling basin had a capacity of approximately 6,813 m^3 (1.8 million gallons). The secondary settling basin capacities were 2,744 m^3 (0.725 million gallons).

Chlorine and alum were added before primary settling with average concentrations of 6 and 28 mg/L, respectively. A free chlorine residual of 1.5 - 2.0 mg/L was maintained after sand filtration with any make-up chlorine being added before the water passed into a common clearwell. Approximately 12 mg/L of lime was added after primary settling for pH adjustment to 8.0 and about 1.5 mg/L of fluoride was added immediately before the rapid mixed media filters.

Pilot Plant (Figure 5)

A 0.38 m^3/min (100 gpm) pilot plant* with a detention time of approximately 37 minutes was used for extensive evaluations. Disinfection was accomplished by on-site generation of chlorine dioxide. Average alum and polymer dosages of 12 and 0.8 mg/L, respectively were added to the raw water for turbidity control. For pH control to about 8.0, an average lime dosage of approximately 6.0 mg/L was added prior to filtration.

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*Neptune Microfloc Waterboy®

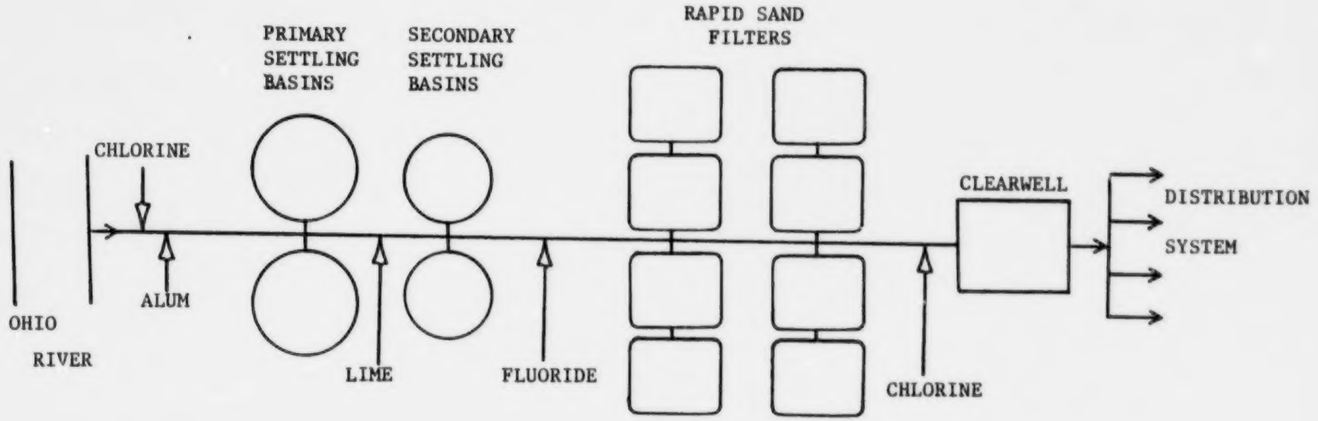

PRIMARY SETTLING BASINS
SECONDARY SETTLING BASINS
RAPID SAND FILTERS
CHLORINE
CLEARWELL
DISTRIBUTION SYSTEM
OHIO RIVER
ALUM
LIME
FLUORIDE
CHLORINE

FIGURE 4. FLOW DIAGRAM OF EVANSVILLE, INDIANA FULL-SCALE SOUTH PLANT

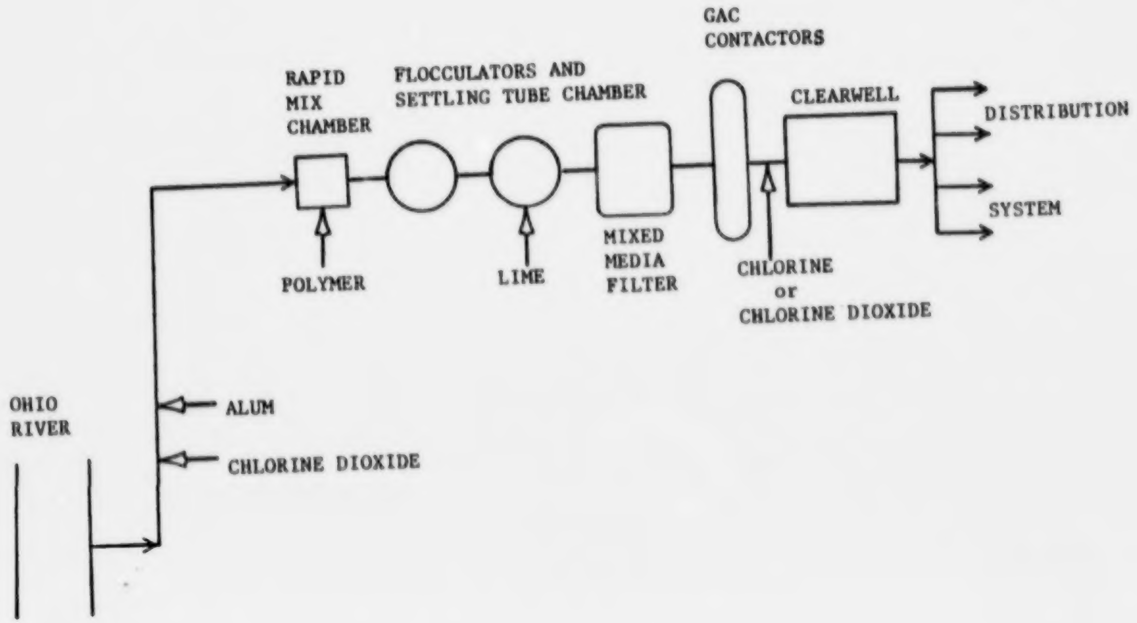

RAPID
MIX
CHAMBER
FLOCCULATORS AND
SETTLING TUBE CHAMBER
GAC
CONTACTORS
CLEARWELL
DISTRIBUTION
SYSTEM
POLYMER
LIME
MIXED
MEDIA
FILTER
CHLORINE
or
CHLORINE DIOXIDE
OHIO
RIVER
ALUM
CHLORINE DIOXIDE

FIGURE 5. SCHEMATIC DIAGRAM OF EVANSVILLE, INDIANA
PILOT PLANT

The pilot plant consisted of a rapid mix chamber, flocculator, tube settlers, and mixed media filter. Two post pilot plant GAC contactors were used that had a column height of 2.7 m (9.0 ft), and inside diameter of 0.97 m (38 in), and an average GAC bed depth of 2.0 m (6.5 ft). An EBCT of 9.6 minutes was established with a hydraulic loading of 12.2 m/hr (5.1 gpm/ft^2).

The GAC used in this study was ICI Hydrodarco® 10 x 30.

E. Miami, Florida(7)

Full-Scale Treatment Plant (Figure 6)

The John E. Preston Water Treatment Plant, located in Hialeah, Florida, is one of three water plants serving the greater Miami area. This plant was operated by the Miami-Dade Water and Sewer Authority. The rated capacity of the plant was 2.63 m^3/s (60 mgd) and was operated near capacity. Raw water was supplied from seven wells, each approximately 27.4 m (90 ft) deep, to three upflow Hydrotreator® softeners where approximately 200 mg/L of lime was added. Activated silica (1.6 mg/L) was fed to the Hydrotreator® influent. After recarbonation, 18 mg/L of chlorine was added to the Hydrotreator® and routed to a chlorine contact basin with a retention time of 1.25 hours. Following chlorine contact, the water flowed to twelve rapid sand filters at a rate of 0.22 m^3/s - 7.2 m/hr (5 mgd - 3 gpm/ft^2) and thence to the clearwell before distribution.

Bench Scale Adsorption Unit

A flow diagram for the bench-scale configurations used in the research effort are shown in Figures 7-9. Each glass column was 1.52 m (5 ft) long by 2.54 cm (1 in) in internal diameter. A flow rate of 7.2 m/hr (3 gpm/ft^2) was maintained by rotameters.

F. ORSANCO (Huntington, West Virginia and Beaver Falls, Pennsylvania)(8)

1. Huntington, West Virginia

Full-Scale Treatment Plant (Figure 10)

Raw source water from the Ohio River, under normal operating conditions, was coagulated by the addition of 8.6 - 34.2 mg/L of ferric sulfate and the pH was adjusted by 10.8 - 42.8 mg/L of lime. No other chemical addition to the raw water was practiced except under unusual circumstances.

Three to five mg/L of chlorine was added before settling and 1.5 - 2.5 mg/L before discharge to the distribution system. Depending upon the normal fluoride concentration in the raw water (usually 0.1 - 0.3 mg/L), an additional dosage of 0.7 - 0.9 mg/L was added to obtain a 1 mg/L concentration.

Although no GAC pilot studies were conducted to select the optimum GAC or bed depth for organics control, Westvaco's WVW® 14 x 40 GAC was evaluated based on its effective taste and odor control at the utility. Virgin

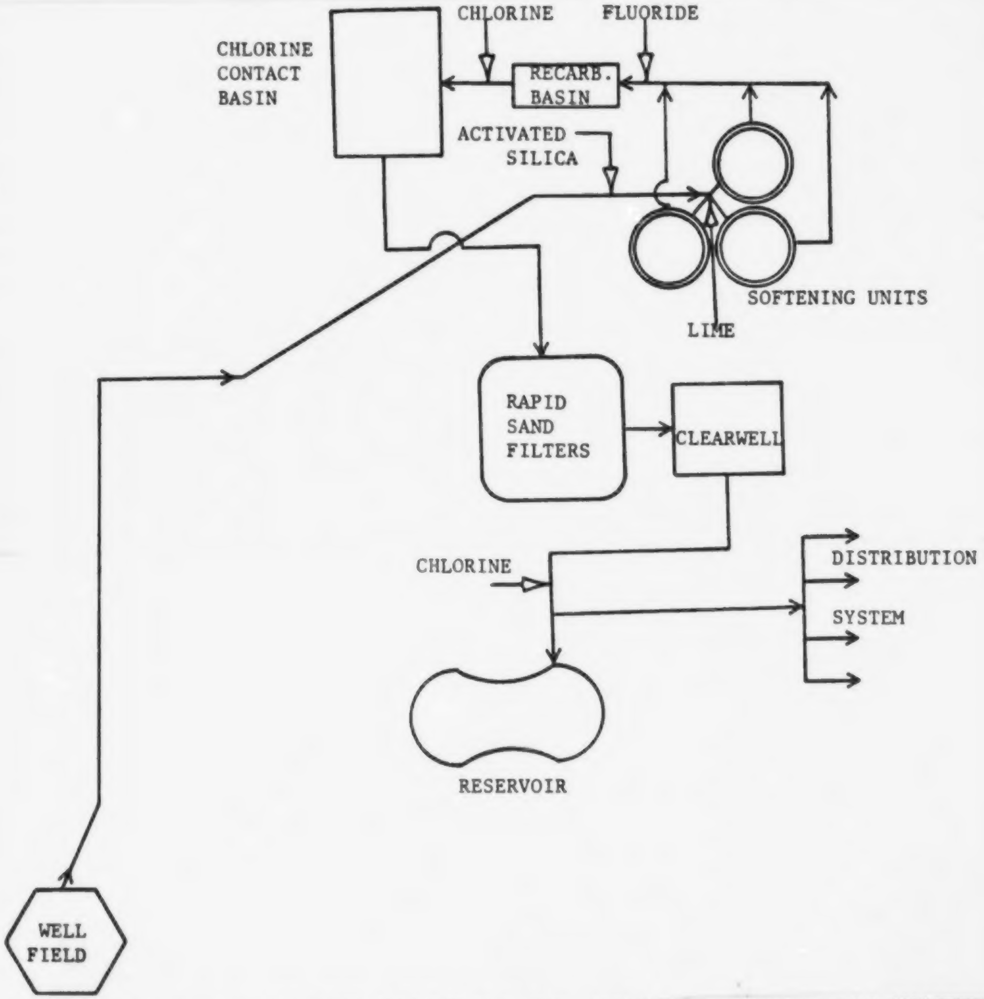

CHLORINE
FLUORIDE
CHLORINE CONTACT BASIN
RECARB. BASIN
ACTIVATED SILICA
SOFTENING UNITS
LIME
RAPID SAND FILTERS
CLEARWELL
CHLORINE
DISTRIBUTION SYSTEM
RESERVOIR
WELL FIELD

FIGURE 6. FLOW DIAGRAM OF JOHN E. PRESTON WATER TREATMENT PLANT IN MIAMI, FLORIDA

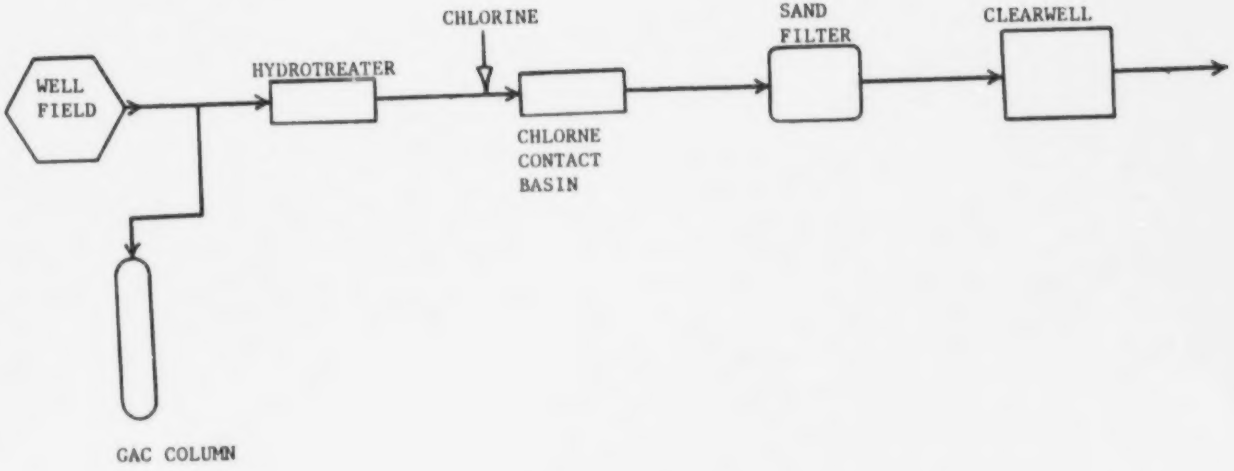

CHLORINE
SAND
FILTER
CLEARWELL
WELL
FIELD
HYDROTREATER
CHLORNE
CONTACT
BASIN
GAC COLUMN

FIGURE 7. FLOW DIAGRAM OF RAW WATER INFLUENT TO BENCH SCALE GAC ADSORPTION FOR MIAMI, FLORIDA

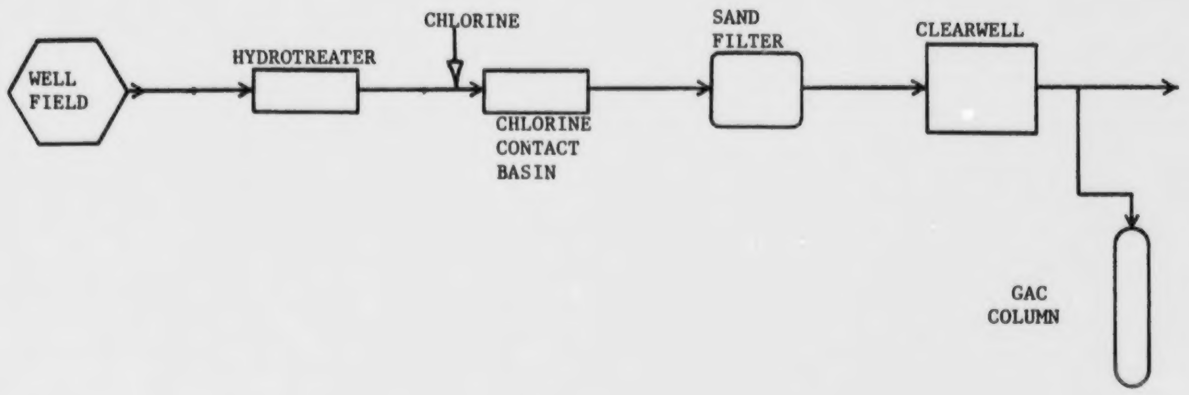

WELL FIELD
HYDROTREATER
CHLORINE
CHLORINE CONTACT BASIN
SAND FILTER
CLEARWELL
GAC COLUMN

FIGURE 8. FLOW DIAGRAM OF CLEARWELL INFLUENT TO BENCH SCALE GAC ADSORPTION IN MIAMI, FLORIDA

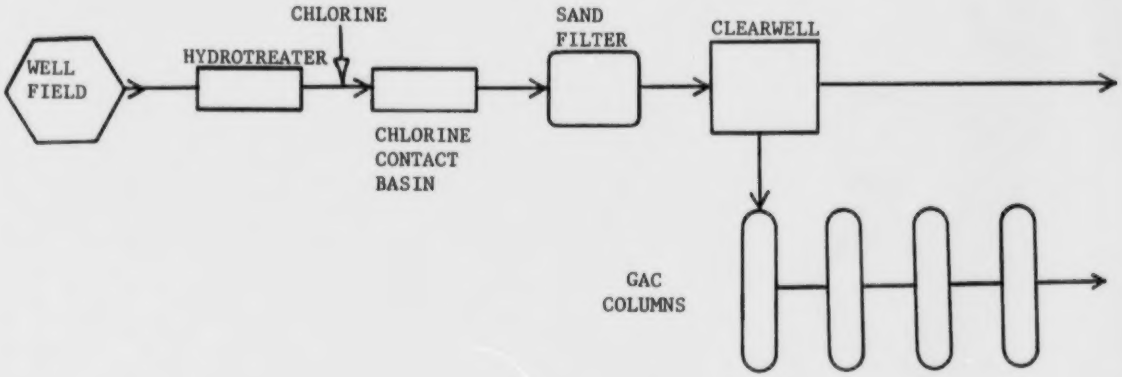

CHLORINE
SAND FILTER
CLEARWELL
WELL FIELD
HYDROTREATER
CHLORINE CONTACT BASIN
GAC COLUMNS

FIGURE 9. FLOW DIAGRAM OF BENCH SCALE ADSORPTION FOR DEEP BED GAC STUDY IN MIAMI, FLORIDA

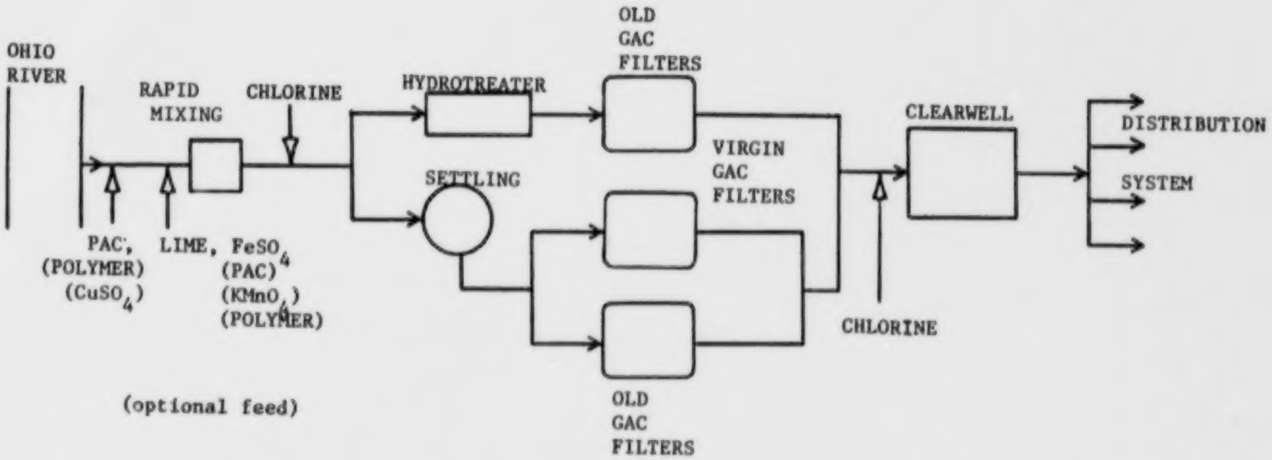

OHIO RIVER
RAPID MIXING
CHLORINE
HYDROTREATER
OLD GAC FILTERS
SETTLING
VIRGIN GAC FILTERS
CLEARWELL
DISTRIBUTION SYSTEM
PAC, (POLYMER) (CuSO4)
LIME, FeSO4 (PAC) (KMnO4) (POLYMER)
CHLORINE
OLD GAC FILTERS
(optional feed)

FIGURE 10. TREATMENT SCHEME FOR HUNTINGTON WATER CORPORATION IN HUNTINGTON, WEST VIRGINIA

GAC was used in a filtration/adsorption mode in a sand replacement bed. The bed was placed in service with 76 cm (30 in) of GAC on top of 30 cm (12 in) of sand and gravel. The mean hydraulic loading rate was 6.1 m/hr (2.6 gpm/ft^2) and the mean EBCT was 7.2 minutes. Additional data were collected on older (one and two-and-one-half year old) filter/adsorber beds to evaluate performance over longer periods of operation.

2. Beaver Falls, Pennsylvania

Full-Scale Treatment Plant (Figure 11)

Raw source water for the Beaver Falls water treatment plant was supplied by the Beaver River. Primary coagulation of this water was accomplished by a liquid alum dose of about 21 mg/L. Occasionally, potassium permanganate was added at a dose of 2.0 mg/L when not going to breakpoint. Secondary coagulation and pH adjustment was accomplished by about 25 mg/L of lime. Also added before secondary settling for breakpoint was about 9.0 mg/L of chlorine.

About 0.7 mg/L of fluoride was added to the secondary settled water to produce a final concentration of 1.0 mg/L. When used, about 14 mg/L of PAC was also added to the secondary settled water. Post filter effluent (sand and GAC) was disinfected on the average with an applied dose of 0.5 mg/L chlorine and 0.1 mg/L of chlorine dioxide.

Two beds of virgin GAC were evaluated in the filtration/adsorption mode. A third bed contained Filtrasorb C®, a special Calgon product formulated for trihalomethane adsorption. One GAC bed contained 61 cm (24 in) of Calgon's Filtrasorb 400® placed on top of 30 cm (12 in) of sand and gravel. The second GAC bed contained 61 cm (24 in) of ICI's Hydrodarco® 8 x 16 placed on top of 30 cm (12 in) of sand and gravel. The filter/adsorbers were geometrically identical except the Calgon unit was designed with a tile bottom, while the ICI unit had a porous plate bottom. Hydraulic data for each unit are presented in Table 1.

TABLE 1. HYDRAULIC DATA (MEAN VALUES), BEAVER FALLS, PA

	GAC	
Parameter	Filtrasorb 400®	Hydrodarco® 8x16
Loading rate, m/hr	3.1	3.1
(gpm/ft^2)	(1.3)	(1.3)
Empty bed contact time, minutes	11.3	11.4
GAC depth, cm	61	61
(inches)	(24)	(24)
	30	30
Sand and gravel depth, cm	30	30
(inches)	(12)	(12)

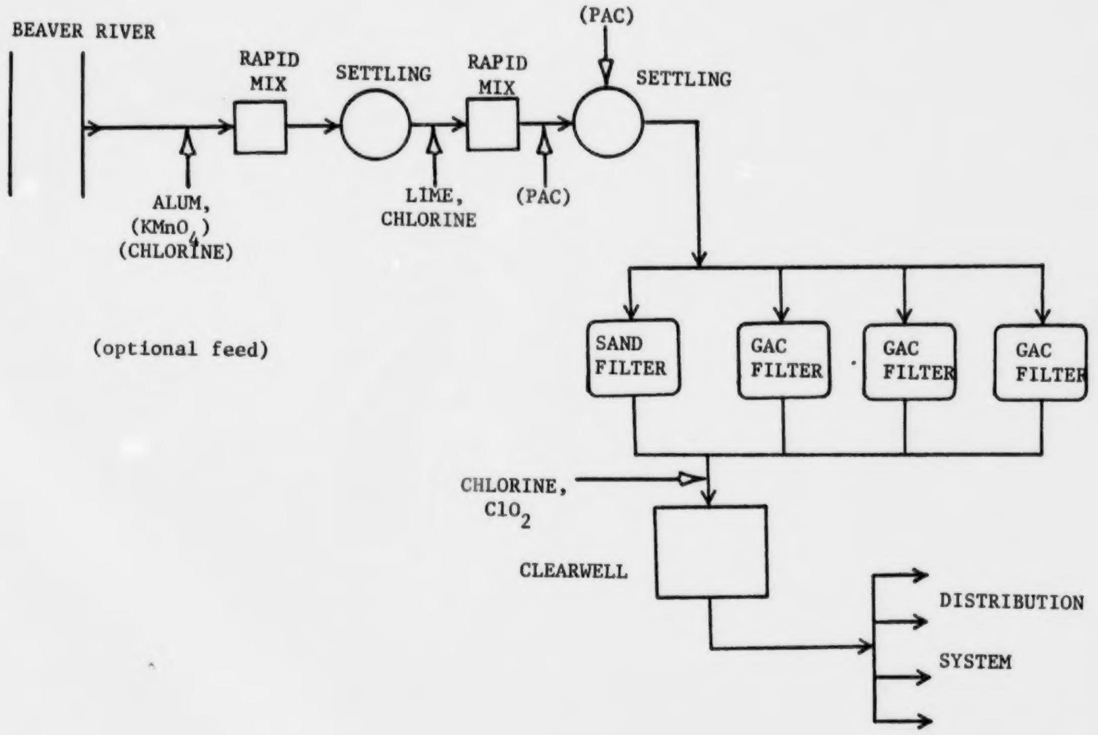

BEAVER RIVER
RAPID MIX
SETTLING
RAPID MIX
(PAC)
SETTLING
ALUM, (KMnO$_4$) (CHLORINE)
LIME, CHLORINE
(PAC)
(optional feed)
SAND FILTER
GAC FILTER
GAC FILTER
GAC FILTER
CHLORINE, ClO$_2$
CLEARWELL
DISTRIBUTION
SYSTEM

FIGURE 11. WATER TREATMENT SCHEME FOR BEAVER FALLS AUTHORITY, PENNSYLVANIA

G. Passaic Valley, Little Falls, New Jersey (Figure 12)(9)

The Little Falls Filtration plant source water was supplied by the Passaic River. This plant employed prechlorination, alum coagulation, settling, filtration (anthracite coal over sand) and dechlorination by sulfur dioxide. During the study an average of 28.2 mg/L of alum and 16.0 mg/L of chlorine were added prior to the raw water pumps. Sulfur dioxide at an average concentration of 0.9 mg/L was added after the settling basin prior to filtration. For pH control sodium hydroxide (average of 27.6 mg/L) and post disinfection chlorine (0.5 mg/L average) were added to the clearwell effluent. Average flow of the 378,500 m^3/day (100 mgd) designed plant was 208,000 m^3/day (55 mgd).

A portion of the treated water (7,192 m^3/day or 1.9 mgd) that is normally distributed to the consumer was pumped to three cylindrical pressure GAC contactors. Each contactor was 8.5 m (28 ft) high and 2.4 m (8 ft) in diameter with an EBCT of approximately 8 minutes. GAC from three different manufacturers was evaluated simultaneously in the pressure contactors. The carbons consisted of ICI Hydrodarco® 10 x 30, Westvaco WVW® 12x40, and Calgon Filtrasorb 400®.

H. Thornton, Colorado

Full-Scale Treatment Plant (Figure 13)(10)

Two water treatment plants were available to the City of Thornton for treating their drinking water. One plant was the 15 mgd Thornton plant and the other one was the 20 mgd Columbine plant. The full-scale plant evaluated during the research project was the Columbine plant because of the contaminants in its raw water sources.

A major portion of Columbine's raw water was directly influenced by the Denver Metro Sewage Treatment Plant and various industrial dischargers. These discharges were into the South Platte River that infiltrated into various gravel lakes and wells located adjacent to the river. Columbine's raw water was drawn from these lakes and wells.

Potassium permanganate (0.4 to 0.6 mg/L) was added to the raw water for iron and manganese removal. For coagulation, ferric chloride was used at a concentration that varied from 5 to 20 mg/L. Breakpoint chlorination was accomplished by chlorine doses that at times ranged up to 50 mg/L. After premix, 2 to 4 mg/L of PAC was added for taste and odor control and some free chlorine removal. After PAC, lime was added for pH control to 8. Following clarification, the water was chlorinated and filtered through eight dual-media filters.

Pilot Plant (Figure 14)

A 10 gpm pilot plant consisting of a raw-water rapid-mix chamber, two-stage flocculation, settling basin, dual-media filter and water storage chamber was used to simulate full-scale treatment. A portion of the raw

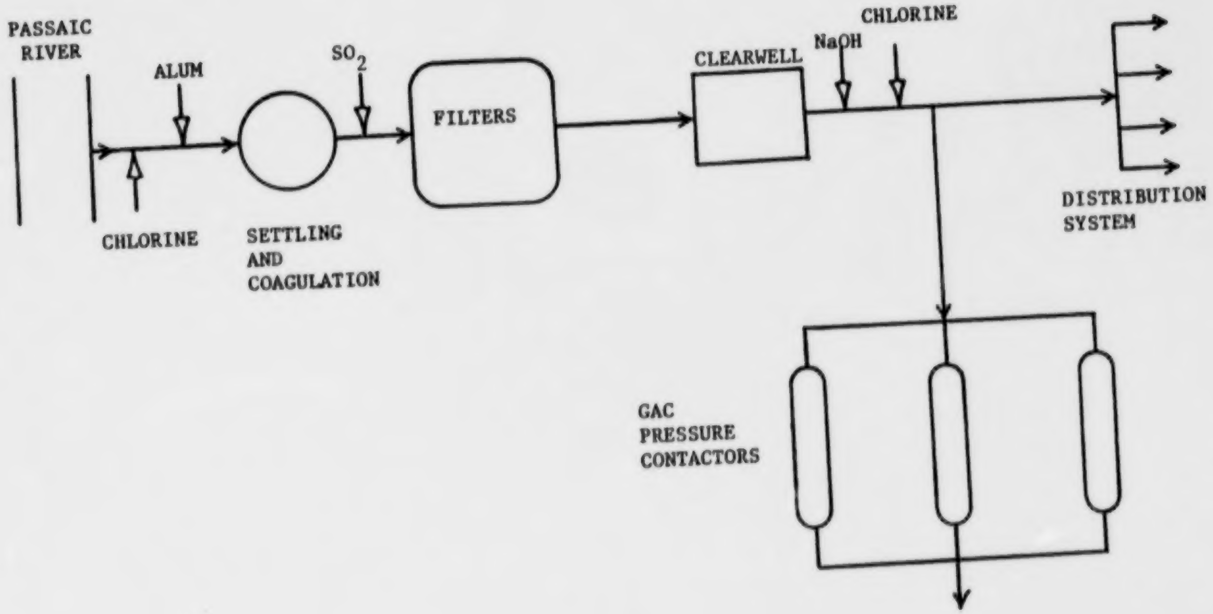

PASSAIC
RIVER
ALUM
CHLORINE
SETTLING
AND
COAGULATION
SO2
FILTERS
CLEARWELL
NaOH
CHLORINE
DISTRIBUTION
SYSTEM
GAC
PRESSURE
CONTACTORS

FIGURE 12. FLOW SCHEMATIC OF LITTLE FALLS, NEW JERSEY FILTRATION PLANT

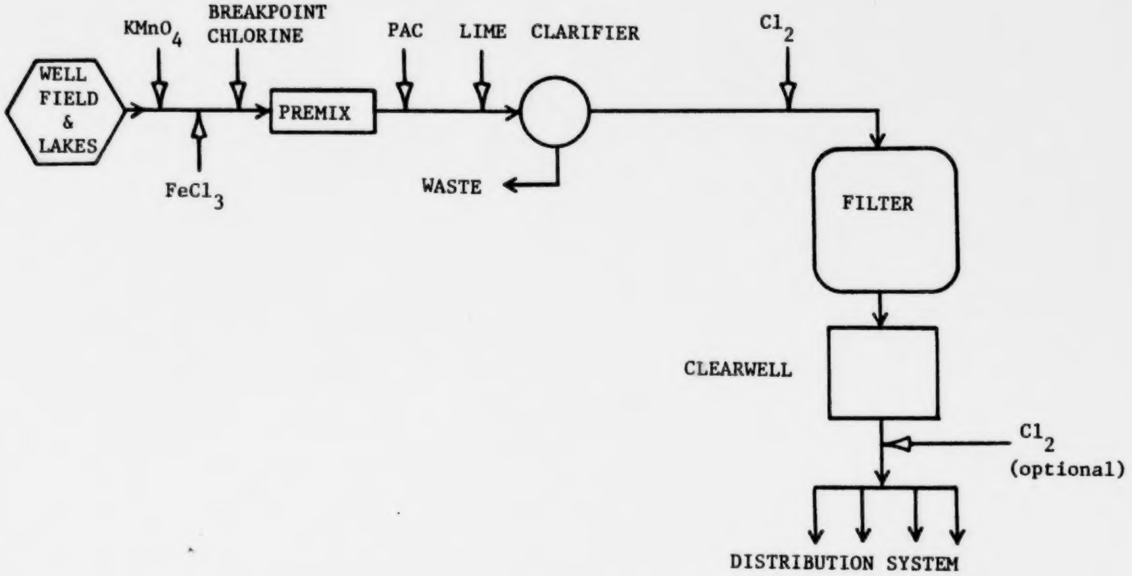
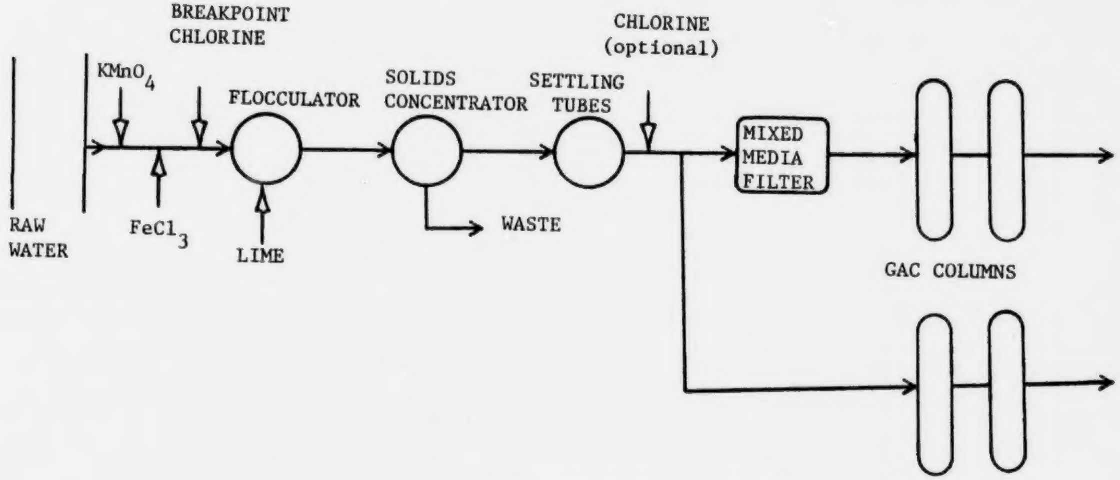

WELL
FIELD
&
LAKES
$KMnO_4$
BREAKPOINT
CHLORINE
$FeCl_3$
PREMIX
PAC
LIME
CLARIFIER
WASTE
Cl_2
FILTER
CLEARWELL
Cl_2
(optional)
DISTRIBUTION SYSTEM

FIGURE 13. FLOW DIAGRAM OF COLUMBINE WATER TREATMENT PLANT FOR THORNTON, COLORADO



BREAKPOINT CHLORINE
CHLORINE (optional)
KMnO$_4$
FLOCCULATOR
SOLIDS CONCENTRATOR
SETTLING TUBES
MIXED MEDIA FILTER
RAW WATER
FeCl$_3$
LIME
WASTE
GAC COLUMNS

FIGURE 14. PILOT PLANT FLOW DIAGRAM FOR THORNTON, COLORADO

EPA Form 2250-4 (4-80)
(PREVIOUSLY EIN. EPA FORM 287)
TYPING GUIDE SHEET

water going to the full-scale Columbine plant was divereted to the pilot plant. Before filtration a portion of the water was diverted to two GAC columns in series. Also, after filtration a portion of the water again was directed to two GAC columns in series. This provided the opportunity to evaluate combined filtration/adsorption and post-filtration adsorption.

Each of the four GAC columns were 15.2 cm (6 in.) in diameter and 2.4 m (8 ft) tall with an effective depth of 1.7 m (5.5 ft) of Westvaco® 12 x 40 GAC. The EBCT for each column was 10 minutes at a hydraulic loading rate of 9.6 m/hr (4 gpm/ft^2) at a flow of 3.0 Lpm (0.8 gpm).

Organic Parameters Analyzed

Although all of the field projects had a common objective to evaluate the effectivenss of GAC for removal of organic contaminants from drinking water, they were somewhat different in their approach. Also, in most cases, different sources of raw water were evaluated. Therefore, the same constituents were not present at all locations.

Sampling generally consisted of the raw source water, coagulated/settled water, sand filter effluent, and GAC effluent. Listed in Table 2 is a combination of all of the different organic compounds that were in the analytical scheme for the nine projects. Not all of these compounds were detected. In addition to these specific compounds, general parameters such as TOC and TOX were analyzed.

TABLE 2. SPECIFIC ORGANICS EVALUATED DURING GAC PROJECTS

COMPOUND	LOCATION*
Acenaphthene	MI, JP, EV
Acenaphthylene	EV
Acentonaphthone-2'	JP
Acrolein	EV
Acrylonitrile	EV
Aldrin	CW, JP, EV, MI, PA, O
Aniline	CW
Anthracene	EV, JP
Atrazine	JP
Benzene	CW, EV, JP, MI
Benzidine	CW, EV
Benzo (A) Anthracene	EV
Benzo (K) Fluoranthrene	EV
Benzofluoranthene-3,4	EV
Benzonitrile	JP
Benzo (G,H,I) Perylene	EV
Benzo (A) Pyrene	EV
Benzyl Cyanide	JP
Biphenyl	JP
Bis (2-Chloroethyl) Ether	EV, O
Bis (2-Chloroisopropyl) Ether	EV, O
Bis (2-Chloroethoxy) Methane	EV
Bis (2 Ethyl Hexyl) Phthalate	CW, EV, JP
Bromochloromethane	JP
Bromo Phenyl Ether, 4	EV, O
Butyl Benzyl Phthalate	CW, EV
N-Butyl Isobutyl Phthalate	CW
Carbon Tetrachloride	CW, EV, JP, MI, PA, O
Alpha Chlordane	JP
Chlordane	EV, MI
Gamma Chlordane	JP, PA
Alpha Chlordene	JP
Beta Chlordene	JP
Gamma Chlordene	JP
Chlorobenzene	CW, EV, JP, MI, O
Chloro-M-Cresol, P	EV
Chloroethane	EV
Chlorophenyl Phenyl Ether-4	O
Dichloroethene-Trans-1,2	PA
Chloronaphthalene-2	O
1-Chloro-2Nitrobenzene	JP
Chlorotoluene-P	MI
Dimethyl-2,3,5,6-Tetrachlorotere Phthalate	JP
DDD	O
Ortho Para'-DDD	JP

TABLE 2. (Cont'd)

COMPOUND	LOCATION*
Meta, PARA'-DDD	JP
Para, Para'-DDD	JP
DDE	O
Ortho, Para'-DDE	JP, PA
Para, Para'-DDE	JP
DDT	O
Ortho, Para'-DDT	JP, PA
Para, Para'-DDT	EV, JP, PA
Decanal	CW
Decane-N	JP
Dibenzo (A,H) Anthracene	PA
Dibromoethane-1,2	PA
Dibromomethane	CW, EV, JP
Di N-Butyl Phthalate	EV, MI, PA
Dichlorobenzene, Summation of -M, -O, -P	MI
Dichlorobenzene-Meta	EV, JP, MI, O
Dichlorobenzene-Ortho	CW, EV, MI, O
Dichlorobenzene-Para	EV, MI, CW, O
Dichlorobenzidine-3,3	CW, EV
Dichlorodifluoromethane	EV
Dichloroethane-1,1	O
Dichloroethane-1,2	CW, EV, JP, MI, PA, O
Dichloroethene-1,1	EV, MI, PA
Dichloroethene-Cis-1,2	EV, MI, JP
Dichloromethane	CW, JP
Dichlorophenol-2,3	EV
Dichloropropane-1,2	EV, O
Dichloropropene-1,3,Cis	O
Dichloropropene-1,3,Trans	O
Dichloropropylene-1,3	EV
Dieldrin	EV, JP, MI, PA, O
Diethyl Phthalate	CW, EV, JP
Diiodomethane	PA
Di-Isobutyl Phthalate	CW, JP, MI
Dimethylbenzene-1,3 & 1,4	CW
Dimethylbenzene-1,2	CW
Dimethyl Phenol-2,4	EV
Dimethyl Phthalate	CW, EV, JP
Dimethyl Pyrene-2,4	CW
Dinitro-O-Cresol-4,6	EV
Dinitrophenol-2,4	EV
Dinitrotoluene-2,4	CW, EV
Dinitrotoluene-2,6	CW, EV
Di-Noctyl Phthalate	CW
Diphenylhydrazine-1,2	CW, EV
Dipropyl Phthalate	JP

TABLE 2. (Cont'd)

COMPOUND	LOCATION*
Dodecane-N	JP
Eicosane-N	JP
Endosulfan-1	JP
Endosulfan-2	JP
Endrin	EV, JP, PA
Ethyl Benzene	CW, EV, JP
Ethyl Benzoate	EV, MI
Fluoranthene	EV, JP, MI
Fluorene	EV, JP, MI
Heptachlor	MI, PA, O
Heptachlor Epoxide	EV, MI, PA, O
Heptadecane-N	JP
Hexachlorobenzene	EV, JP, MI
Hexachlorobutadiene	EV, O
Hexachlorocyclohexane (Alpha Benzene Hexachloride)	EV, JP, MI, PA, O
Hexachlorocyclohexane (Beta Benzene Hexachloride)	EV, JP, PA, O
Hexachlorocyclohexane (Delta Benzene Hexachloride)	EV, O
Hexachlorocyclohexane (Gamma Benzene Hexachloride) - Lindane	EV, JP, MI, O
Hexachlorocyclopentadiene	EV
Hexachloroethane	CW, EV, O
Hexadecane-N	JP
Hexane	CW
Indeno (1,2,3-C,D) Pyrene	EV
Isophorone	CW, EV, JP
Methoxychlor	EV, JP, PA
Methylbenzene-1-Ethyl-2	CW
Methylbenzene-1-Ethyl-4	CW
Methyl Bromide	EV
Methyl Chloride	EV, MI
Methylene Chloride	EV, MI, PA
Methylnaphthalene	CW, JP
Mirex	JP, PA
Naphthalene	CW, EV, JP, MI
Nitrobenzene	CW, EV, JP
Nitrophenol-2	EV
Nitrophenol-4	EV
N-Nitroso Di-N-Propylamine	EV
N-Nitroso Dimethylamine	EV
N-Nitroso Diphenylamine	EV
Nitrotoluene-2	EV, JP, MI
Nonadecane-N	JP
Nonanal	CW

TABLE 2. (Cont'd)

COMPOUND	LOCATION*
Octadecane-N	JP
Oxy-Chlordan	EV, JP, MI
Polychlorinated Biphenyl 1016	PA
Polychlorinated Biphenyl 1242	PA
Polychlorinated Biphenyl 1248	PA
Polychlorinated Biphenyl 1254	MI, PA, MI
Pentachloronitrobenzene	EV, JP, MI
Pentachlorophenol	EV
Pentadecane-N	JP
Perthane	JP
Phenanthrene	EV, JP, MI
Phenol	EV, JP
Photodieldrin	JP
Propylbenzene	CW
Pyrene	EV, JP, MI
Pyridine	CW
Tetrachlorodibenzodioxin	EV
Tetrachloroethane-1,1,2,2	CW, EV, JP, PA
Tetrachloroethylene	EV, JP, MI, PA
Tetrachloromethane	JP
Tetradecane-N	JP
Tetralin	CW
Tetramethylbenzene-1,2,3,5	CW
Toluene	CW, EV, JP, MI
Toxaphene	EV, PA
Trichlorobenzene (1,3,5 -1,2,4-1,2,3)	CW, EV, PA, O
Trichloroethane-1,1,1 (Also Methyl Chloroform)	CW, EV, MI, PA, O
Trichloroethane-1,1,2	JP, PA
Trichloroethene (Also Trichloroethylene)	CW, EV, JP, MI, P
Trichlorofluoromethane	EV
Trichlorophenol-2,4,6	EV
Trichlorophenoxy Acetic Acid-2,4,5	EV
Trichlorophenoxy Acetic Acid-2,5,5	EV
Tridecane-N	JP
Trimethylbenzene-1,2,4	CW
Trimethyl-1-Penten-2,2,4	CW
Triphenylmethane	JP
Undecanal	CW
Undecane-N	JP
Vinyl Chloride	MI, PA, JP
Xylene	CW, EV

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*CW - Cincinnati Water Works
EV - Evansville
JP - Jefferson Parish (I)
MA - Manchester
MI - Miami (I)
O - ORSANCO (Huntington, Beaver Falls)
PA - Passaic
TH - Thornton

SECTION IV

VIRGIN CARBON PERFORMANCE FOR EACH PROJECT

GAC Selection

Various types of GAC were used at the nine locations with selection based on different reasons. The major reason for selecting a particular GAC was economics. Normally, a low bidder was chosen. There were, however, occasions when a GAC type had not been evaluated and a determination was made to forego the bidding process in favor of a pre-selected GAC. Also, for some projects, a GAC was selected based on performance when evaluated in parallel with various other types of GAC.

Individual Project Evaluations

Because different GACs were evaluated, they will be examined separately in this section. Also, different parameters were detected at various locations making individual project evaluations necessary.

Jefferson Parish, Louisiana

Several different operational modes were evaluated at Jefferson Parish; namely adsorption, filter/adsorption, and pilot column simulation. Adsorption performance (adsorber) will be presented in this section and the others discussed later.

The adsorber consisted of 30 inches of Westvaco WV-G® 12 x 40 GAC evaluated for three 6 month operations (Phase I, IIA, IIB). One other 6 month study (Phase III) evaluated Calgon Filtrasorb 400® again using 30 inches of GAC. The adsorber received sand filter effluent after conventional treatment using monochloramine as the predisinfectant. Operating conditions for the four phases are shown in Table 3.

TABLE 3. OPERATING CONDITIONS FOR ADSORBER - JEFFERSON PARISH, LA

Phase	Date	Avg. Flow Rate (gal/day)[1]	Hydraulic Load (gpm/ft^2)[2]	Avg. EBCT (min)
I	2/7/77 - 8/5/77	0.41×10^6	0.75	21.9
IIA	11/4/77 - 4/28/78	0.40×10^6	0.73	23.7
IIB	7/10/78 - 1/10/79	0.59×10^6	1.07	17.0
III	4/6/79 - 10/5/79	0.52×10^6	0.95	18.8

Phase I, IIA, IIB - Westvaco WV-G® 12 x 40
Phase III - Calgon Filtrasorb® 400

[1] gal/day x (0.0438×10^{-6}) = m^3/sec
[2] gpm/ft^2 x 2.4 = m/hr

Although numerous organic parameters (18 volatile and 66 nonvolatile) were monitored, only a few were detected continuously and then at the microgram or nanogran per liter levels. The most prevalent low molecular weight specific organic other than the trihalomethanes was 1,2-dichloroethane. The concentration of this compound was not reduced during conventional treatment.

GAC did, however, remove 1,2-dichloroethane until saturation, whereupon desorption occurred because of temporary decreases in the influent concentration. The occurrence of this desorption varied from 70 to 160 days of GAC filter operation (Figure 15) for applied concentrations ranging from 0.1 to 24 ug/L.

Another prevalent compound in the water at Jefferson Parish was atrazine. This chlorinated herbicide, like 1,2-dichloroethane, was not reduced in concentration during conventional treatment. Raw water concentrations ranged from <0.1 to 5,360 ng/L with variability related to water temperature and seasonal effects. Higher concentrations were noted at higher temperatures (seasonal trend). The GAC adsorber effectively removed atrazine to below detection limits in most cases and no desorption occurred up to 180 days of operation as shown in Figure 16.

Other chlorinated hydrocarbon insecticides (CHI) monitored occurred at average concentrations below 5 ng/L. Therefore, they were combined to evaluate the cumulative GAC adsorption effect. The insecticides included in this evaluation are shown in Table 4 along with their frequency of occurrence for the sand filter effluent (GAC influent). Although the summed CHI concentrations were lower than atrazine concentrations, GAC performance was similar in that the CHI was essentially removed without noticeable desorption after 180 days of operation (Figure 17).

TOC, a general parameter found in all surface water systems was also effectively reduced by GAC. For up to about 100 days of operation steady state conditions occurred for WV-G® 12 x 40 at an influent concentration of 3-4 mg/L of TOC. The Filtrasorb 400® (Phase III) at an influent TOC concentration of about 3 mg/L, however, showed a continual rise in the adsorber effluent levels for 160 days with some indication of steady state after that time of operation (Figure 18 and 19).

The phthalates, n-alkanes, and substituted benzene derivatives in the ng/L level, did not appear to be adsorbed by GAC. Some of these substances did, however, exhibit a low degree of constant removal suggesting natural biological decomposition. The compounds evaluated are presented in Table 5.

Cincinnati, Ohio

Many specific organics were investigated but most were present in low concentrations near the detection limits. For example, Table 6 shows the purgeable halogenated and non-halogenated organics that were detected in the GAC effluent of two contactors. The inability to draw conclusions on GAC effectiveness for removing various specific organics was also compounded

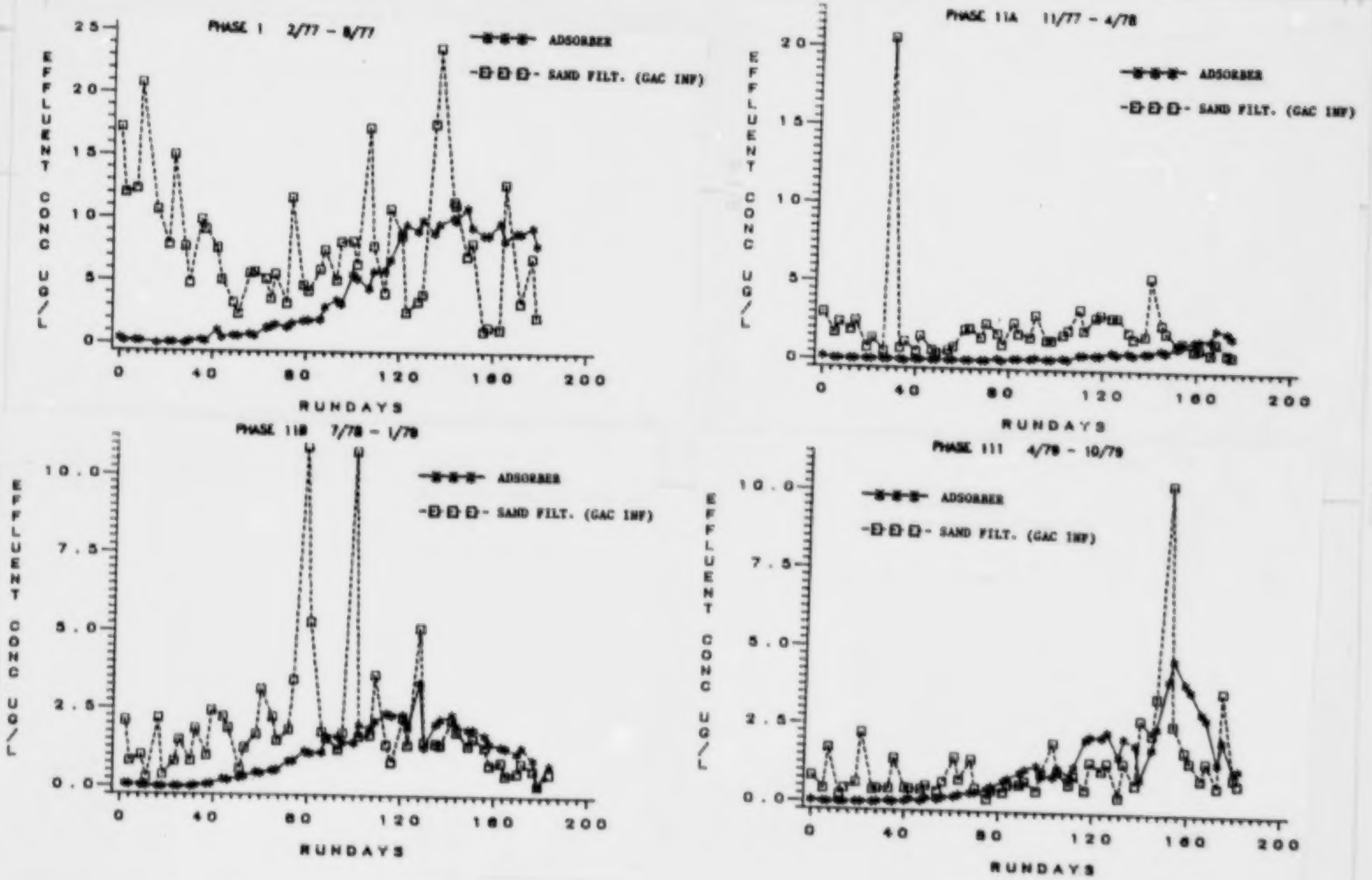


FIGURE 15. CONCENTRATION OF 1,2–DICHLOROTHANE FOR GAC ADSORBER – JEFFERSON PARISH, LOUISIANA

EPA Form 2200-6 (4-80)
TYPING GUIDE SHEET

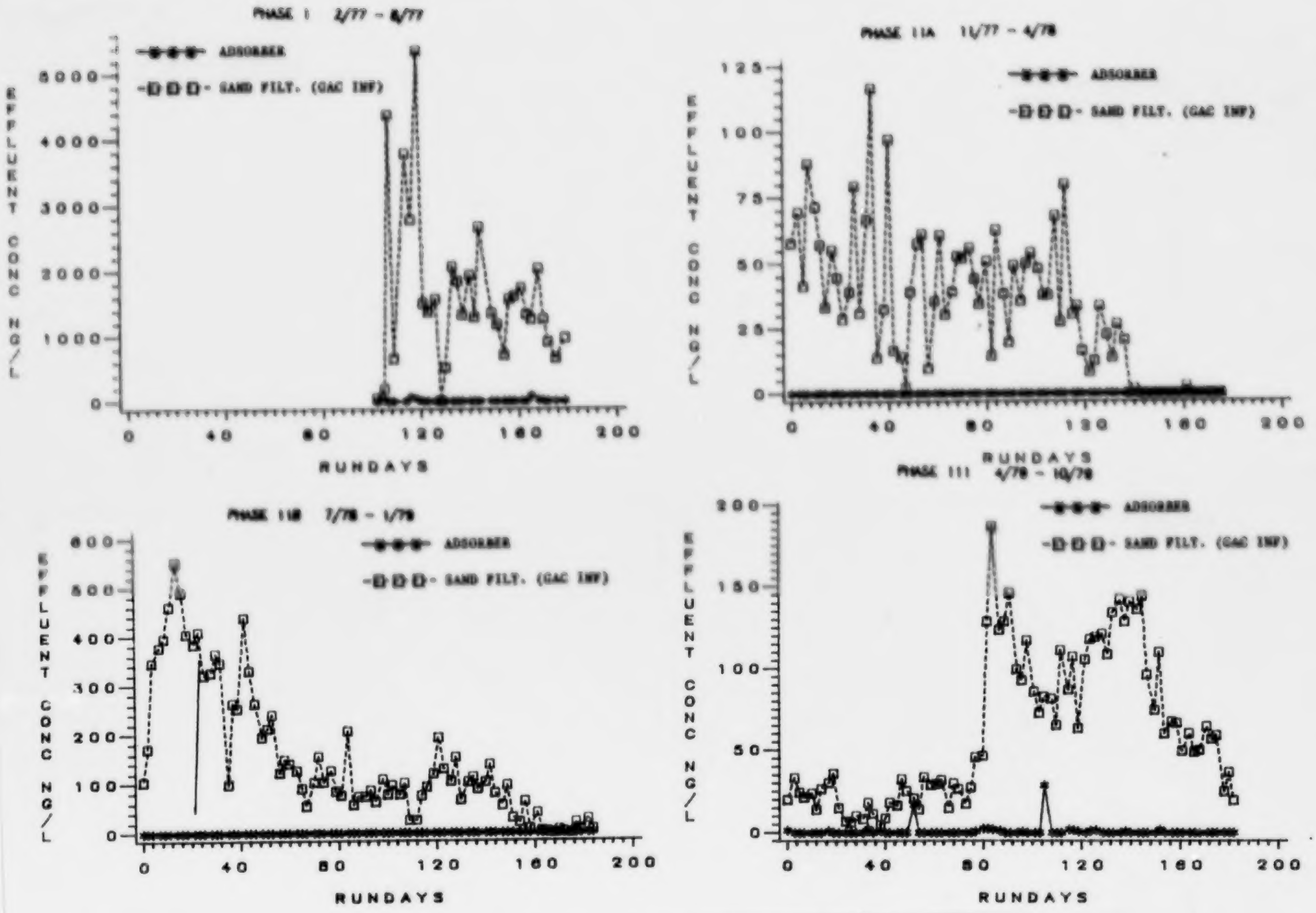


FIGURE 16. ATRAZINE REMOVAL BY GAC ADSORBER
AT JEFFERSON PARISH, LOUISIANA

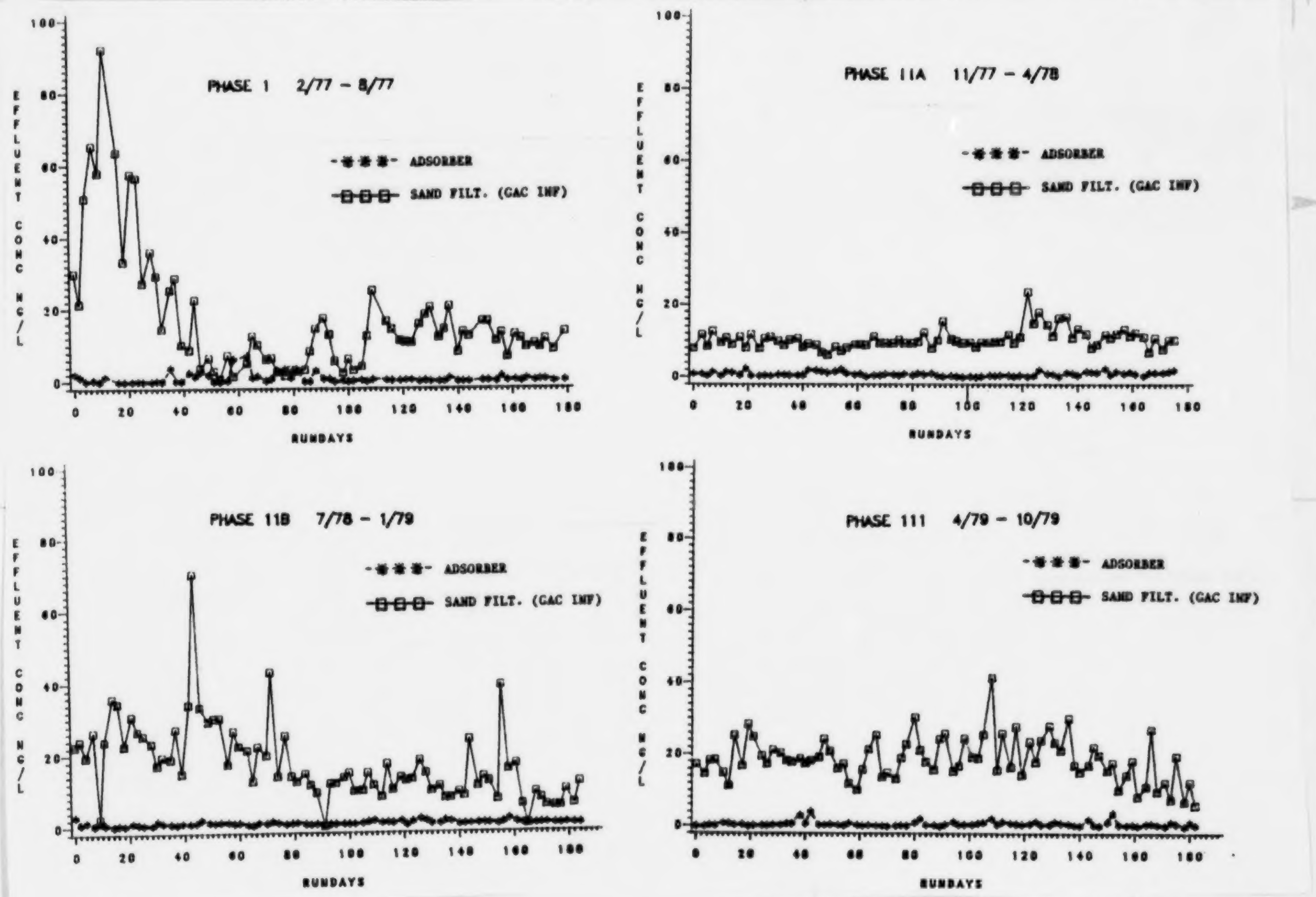


FIGURE 17. GAC ADSORPTION OF SUMMED CHLORINATED HYDROCARBON INSECTICIDES AT JEFFERSON PARISH, LOUISIANA

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN EPA FORM 267)
TYPING GUIDE SHEET

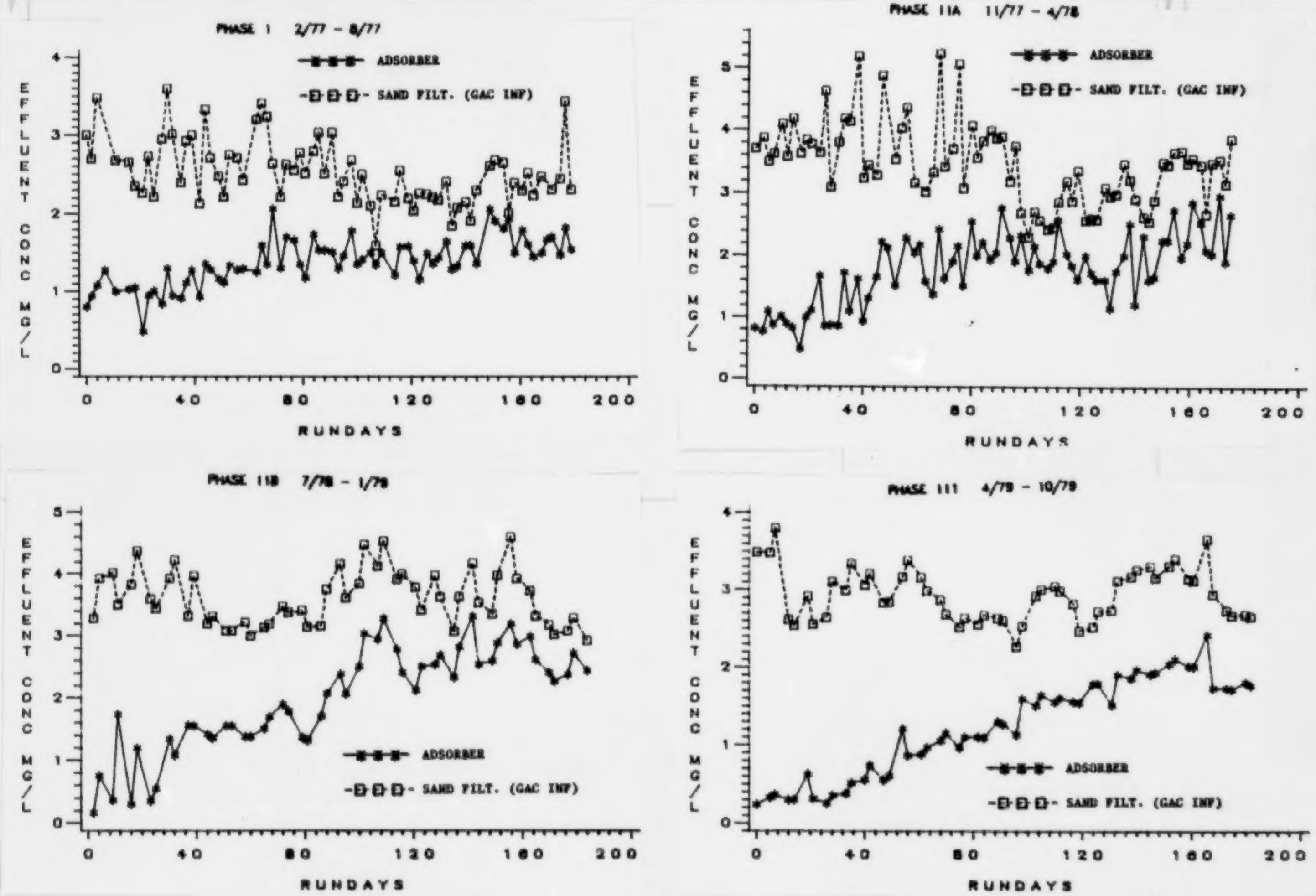


FIGURE 18. GAC ADSORBER PERFORMANCE FOR TOC REDUCTION AT JEFFERSON PARISH, LOUISIANA

EPA Form 2350-4 (1-80)
(PREVIOUSLY CIN. EPA FORM 287)
TYPING GUIDE SHEET

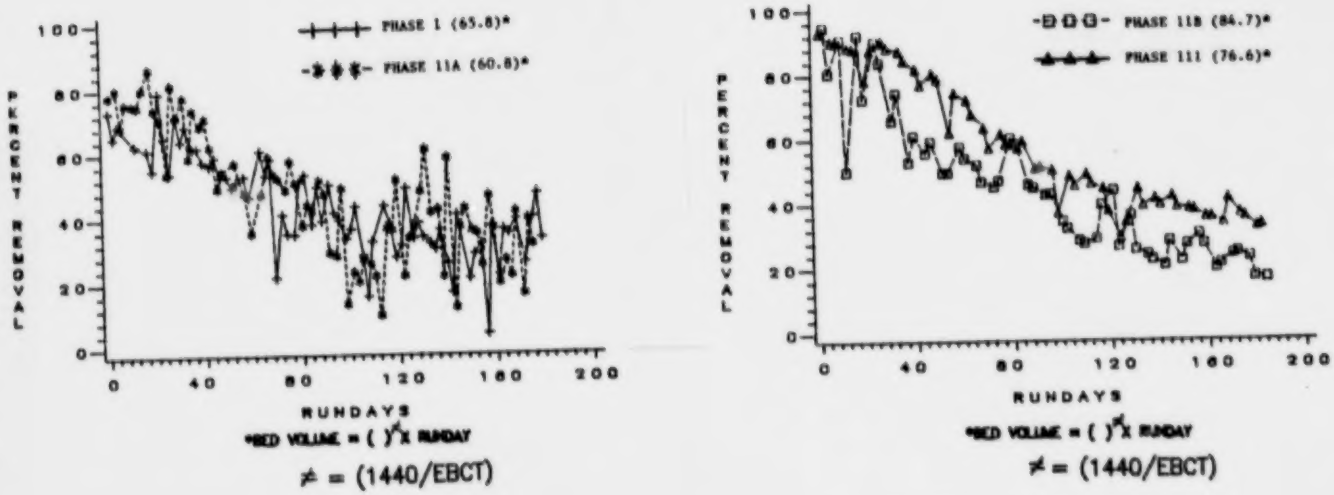


FIGURE 19. PERCENT TOC REMOVAL AT JEFFERSON PARISH, LA.

TABLE 4. FREQUENCY OF OCCURRENCE AND CONCENTRATION RANGES IN THE SAND FILTER EFFLUENT FOR ALL CHLORINATED HYDROCARBON INSECTICIDES MONITORED DURING EACH PHASE - JEFFERSON PARISH, LA

COMPOUND	PHASE I		PHASE IIA	
CHLORINATED HYDROCARBON INSECTICIDES	OBS. FREQ. (%)	CONC. RANGE (NG/L)	OBS. FREQ. (%)	CONC. RANGE (NG/L)
Alpha-BHC	100	0.2-8.4	100	0.9-52.0
Beta-BHC	30	0-10.3	0	0-0
Gamma-BHC	98	0-7.3	100	0.3-5.4
Hexachlorobenzene	97	0-2.0	75	0-2.3
Heptachlor	41	0-2.0	21	0-0.5
Alpha-Chlordene	19	0-1.1	34	0-0.2
Beta-Chlordene	42	0-1.1	28	0-0.5
Gamma-Chlordene	58	0-2.1	42	0-1.9
Aldrin	68	0-0.9	55	0-1.0
Heptachlor Epoxide	91	0-1.5	100	0.2-1.2
Alpha-Chlordane	97	0-1.2	100	0.1-0.7
Gamma-Chlordane	98	0-2.3	100	0.2-0.8
Ortho, Para'-DDE	8	0-0.4	19	0-0.3
Para,Para'-DDE	32	0-0.2	82	0-0.2
Endosulfan-1	16	0-0.2	15	0-0.1
Endosulfan-2	58	0-4.0	35	0-1.6
Dieldrin	100	0.1-11.6	100	0.4-3.4
Ortho,Para'-DDD	13	0-1.3	69	0-0.6
Para,Para'-DDD	32	0-1.7	51	0-0.5
Endrin	100	0.04-8.2	100	0.2-2.9
Ortho,Para'-DDT	6	0-0.9	31	0-0.3
Para,Para'-DDT	39	0-55.5	22	0-2.2
Photodieldrin	61	0-2.9	47	0-1.3
Methoxychlor	47	0-10.7	17	0-16.4
Mirex	36	0-10.4	44	0-2.7
Pentachloronitrobenzene	---	----	---	-----
DCPA	---	----	---	-----
Oxy-Chlordane	---	----	---	-----
Meta,Para'-DDD	---	----	---	-----
Perthane	---	----	---	-----

TABLE 4. (Cont'd)

COMPOUND	PHASE IIB		PHASE III	
CHLORINATED HYDROCARBON INSECTICIDES	FREQ. OBS. (%)	CONC. RANGE (NG/L)	FREQ. OBS. (%)	CONC. RANGE (NG/L)
Alpha-BHC	100	1.0-12.0	100	0.8-4.4
Beta-BHC	1	0-4.8	69	0-12.4
Gamma-BHC	100	0.4-9.1	100	0.3-2.0
Hexachlorobenzene	7	0-8.1	87	0-17.2
Heptachlor	96	0-1.1	68	0-0.3
Alpha-Chlordene	70	0-0.5	2	0-0.2
Beta-Chlordene	63	0-0.2	27	0-0.7
Gamma-Chlordene	23	0-0.2	0	0-0
Aldrin	10	0-2.3	39	0-6.1
Heptachlor Epoxide	100	0.2-3.1	98	0-1.9
Alpha-Chlordane	100	0.3-2.4	100	0.2-1.0
Gamma-Chlordane	100	0.2-1.6	100	0.1-1.0
Ortho,Para'-DDE	76	0-0.5	30	0-1.0
Para,Para'DDE	75	0-0.3	82	0-0.1
Endosulfan-1	0	0-0	0	0-0
Endosulfan-2	0	0-0	64	0-2.2
Dieldrin	100	0.9-7.4	100	1.5-7.1
Ortho,Para'-DDD	87	0-2.6	59	0-1.9
Para,Para'-DDD	55	0-0.4	78	0-0.5
Endrin	100	0.1-8.4	98	0-14.4
Ortho,Para'-DDT	3	0-0.4	8	0-0.3
Para,Para'-DDT	5	0-1.9	22	0-0.2
Photodieldrin	22	0-1.8	16	0-10.7
Methoxychlor	0	0-0	16	0-5.8
Mirex	0	0-0	11	0-6.1
Pentachloronitrobenzene	77	0-0.1	53	0-0.5
DCPA	100	0.1-3.7	98	0-5.8
Oxy-Chlordane	0	0-0	5	0-0.4
Meta,Para'-DDD	0	0-0	12	0-0.9
Perthane	55	0-38.5	0	0-0

by their infrequent occurrence. This was illustrated by GC/MS tentatively identified compounds for the acid extracts* from one of the GAC contactors (Contactor D).

Table 7 shows that of the 45 acid extract compounds identified only seven had a percentage of occurrence that was 30 percent or greater. Of these seven dibromochloromethane, 1,3,5-trimethyl-1,3,5-triazine-2,4-6 (1H, 2H, 3H) trione, nitrobenzene and tributyl ester phosphoric acid appeared to be well adsorbed while 3,3,3-trichloro-1-1-propene, 2-cyclohexene-1-01 and 7-oxabicyclo (4.0.1) heptane removals varied from marginal to not adsorbed.

TABLE 5. PHTHALATES, N-ALKANES, AND SUBSTITUTED BENZENE DERIVATIVES MONITORED DURING EACH PHASE AT JEFFERSON PARISH, LA

COMPOUND	PHASE I FREQ. OBS.(%)	PHASE I CONC. RANGE (NG/L)	PHASE IIA FREQ. OBS.(%)	PHASE IIA CONC. RANGE (NG/L)
PHTHALATES				
Bis [2ethylhexyl] phthalate	64	0-16.5	34	0-435.
Dimethylphthalate	31	0-39.4	18	0-15.2
Diethylphthalate	39	0-40.3	94	40.0-89.4
Dipropylphthalate	6	0-4.2	1	0-0.4
Diisobutylphthalate	28	0-12.9	32	0-25.2
Dibutylphthalate	39	0-172.	93	0-120.
N-ALKANES				
N-Decane	6	0-13.7	42	0-216.
N-Undecane	24	0-15.3	34	0-9.8
N-Dodecane	34	0-15.3	57	0-6.6
N-Tridecane	12	0-2.8	44	0-32.7
N-Tetradecane	8	0-7.6	36	0-1.6
N-Pentadecane	12	0-2.3	42	0-1.6
N-Hexadecane		NA		NA
N-Heptadecane		NA		NA
N-Octadecane		NA		NA
N-Nonadecane		NA		NA
N-Eicosane		NA		NA
SUBSTITUTED BENZENE DERIV.				
Benzonitrile		NA		NA
Benzyl cyanide		NA		NA
2-Nitrotoluene		NA		NA
Ethylbenzoate		NA		NA
Ortho-Chloronitrobenzene		NA		NA
Nitrobenzene	38	0-276.	72	0-82.2
Isophorone	23	0-19.0	55	0-10.9

NA - Not analyzed

*Liquid/liquid extraction with dichloromethane after pH adjustment to 2 with hydrochloric acid.

TABLE 5. (Cont'd)

COMPOUND	PHASE IIB		PHASE III	
	FREQ. OBS.(%)	CONC. RANGE (NG/L)	FREQ. OBS.(%)	CONC. RANGE (NG/L)
PHTHALATES				
Bis [2ethylhexyl] phthalate	96	0-48.0	100	1.1-170.
Dimethylphthalate	3	0-2.6	30	0-8.6
Diethylphthalate	100	6.1-346.	100	4.2-47.0
Dipropylphthalate	2	0-5.1	1	0-0.6
Diisobutylphthalate	77	0-33.3	100	0.8-16.0
Dibutylphthalate	98	0-211.	100	8.0-279.
N-ALKANES				
N-Decane	1	0-4.7	72	0-24.8
N-Undecane	0	0-0	81	0-6.7
N-Dodecane	42	0-116.	89	0-77.6
N-Tridecane	2	0-2.0	39	0-20.0
N-Tetradecane	76	0-29.3	26	0-17.6
N-Pentadecane	48	0-5.4	46	0-20.9
N-Hexadecane	62	0-23.4	79	0-7.4
N-Heptadecane	95	0-18.5	100	1.0-14.1
N-Octadecane	61	0-17.7	84	0-8.3
N-Nonadecane	32	0-3.6	74	0-8.9
N-Eicosane	25	0-11.4	97	0-12.4
SUBSTITUTED BENZENE DERIV.				
Benzonitrile	2	0-9.7	86	0-43.4
Benzyl cyanide	5	0-4.7	68	0-18.6
2-Nitrotoluene	30	0-11.5	93	0-29.8
Ethylbenzoate	1	0-0.5	25	0-9.9
Ortho-Chloronitrobenzene	95	0-230.	100	1.0-193.
Nitrobenzene	95	0-336	88	0-51.3
Isophorone	68	0-41.9	73	0-148.

TABLE 6. PURGEABLE ORGANICS DETECTED IN GAC INFLUENT OR EFFLUENT AT CINCINNATI, OHIO

Compound	Contactor C*						Contactor D*					
Halogenated	Influent (ug/L)			Effluent (ug/L)			Influent (ug/L)			Effluent (ug/L)		
	min	max	avg	min	max	avg	min	max	avg	min	max	avg
Carbon tetrachloride	N	N	N	N	N	N	N	0.2	N	N	N	N
1,1,1-Trichloroethane	N	N	N	N	N	N	N	0.2	N	N	0.2	N
Dichloromethane	N	N	N	N	0.2	N	N	0.6	0.2	N	0.5	0.2
Tetrachloroethylene	N	0.2	N	N	N	N	N	0.2	0.1	N	N	N
Trichloroethene	N	0.2	0.1	N	N	N	N	0.2	0.1	N	N	N
Chlorobenzene	N	N	N	N	N	N	N	0.2	N	N	N	N
O-Dichlorobenzene	N	N	N	N	N	N	N	0.2	N	N	0.2	N
Non-Halogenated												
Benzene	0.2	1.0	0.6	0.2	0.6	0.4	N	1.2	0.3	0.2	0.8	0.3
o-Xylene	N	0.2	N	N	0.2	N	N	N	N	N	N	N
Ethylbenzene	N	0.2	N	N	0.2	0.1	N	13.4	1.7	N	0.8	0.1
Toluene	N	0.9	0.2	N	0.2	N	N	1.2	0.4	0.2	2.8	0.4
Hexane	N	0.6	0.2	N	0.7	0.1	N	1.5	0.2	N	1.0	0.1
Tetralin	N	N	N	N	N	N	N	2.4	0.1	N	0.9	N

N - Not detected (below detection limit of 0.1 ug/L)

* Each contactor had a hydraulic loading of 7.4 gpm/sq ft, EBCT of 15.2 min, and used WV-G® 12 x 40 GAC

TABLE 7. ACID EXTRACT COMPOUNDS TENTATIVELY IDENTIFIED BY GC/MS FROM CONTACTOR D - CINCINNATI, OHIO

	Percent of Occurrence			
Compound	INF[a]	D7[b]	DE[c]	Blank[d]
Dibromochloromethane	70	11	N	N
3,3,3-Trichloro-1-propene	50	22	20	N
1,3,5-Trimethyl-1,3,5-triazine-2,4,6-(1H,2H,3H)-trione	40	N	N	N
7-Oxabicyclo(4.0.1)heptane	30	33	40	10
2-Cyclohexene-1-one	30	22	10	N
Nitrobenzene	30	N	N	N
Tributyl ester phosphoric acid	30	N	N	N
Diethyl ester-1,2-benzenedicarboxylic acid	20	11	20	10
2-Methyl-1,4-dinitrobenzene	20	N	N	N
Tribromomethane	20	N	N	N
Benzoic acid	10	N	N	N
Bromodichloromethane	10	N	N	N
1-Chloro-2-butene	10	N	N	N
Butane	10	N	N	N
Cyclohexene	10	11	N	10
Decycl ester nitric acid	10	N	N	N
1,4-Dichlorobutane	10	11	10	N
1,1-Dichloropropane	10	N	N	N
1,1-Dichloro-2-propanone	10	N	N	N
Dimethyl-1-4-dioxalane	10	N	N	N
1,2-Dimethylpentane	10	N	N	N
Ethylbenzene	10	N	10	N
3-Ethyl-4-methylfurandiene	10	N	N	N
3-Methyl-2-butadiene	10	N	N	10
5-Methylnonane	10	N	N	N
Nitrocyclopentane	10	N	N	N
2-Nitropentane	10	N	N	N
1-Pentyne	10	N	N	N
1-H-Pyrrole	10	11	N	N
1-H-1,2,4-Triazolediamine	10	N	10	N
2,2,3-Trimethylbutane	10	11	N	N
2,2,3-Trimethylpentane	10	N	N	N
Cyclobutanal	N	11	N	N
2-Cyclohexene-1-ol	N	11	N	10
Cyclopropane	N	11	N	N
2,3-Dimethyl-1-butene	N	11	N	N
3,3-Dimethylhexane	N	11	N	N
4-Ethylheptane	N	11	N	N
2-Methylnaphthalene	N	11	10	N

TABLE 7. (Cont'd)

Compound	Percent of Occurrence			
	INF[a]	D7[b]	DE[c]	Blank[d]
2,4,8-Trimethylnonane	N	11	N	N
1,3-Dimethylbenzene	N	N	10	N
2-Hexene-3-one	N	N	10	N
2,2,5-Trimethylhexane	N	N	10	N
Dibutyl ester ethanoic acid	N	N	N	10
2,2 Proanylchloride	N	N	N	10

---

[a] Influent to contactor D - occurrence based on 10 samples

[b] Sample collected after 7 feet of GAC contact - occurrence based on 9 samples

[c] Contactor D effluent (15 feet of GAC) - occurrence based on 10 samples

[d] Redistilled solvent with internal standard added

N = Not detected

Grob closed loop stripping (CLSA) analysis(2) was performed on one GAC contactor (A) influent and effluent samples at startup and at approximately four week intervals for a total of eleven samples. Approximately 225 compounds were identified with an average of 106 on any one date and a range of 84 to 130. Except for the trihalomethanes all concentrations were in the low ng/L range. Tables 8 and 9 present a data summary of the percent removals by GAC for 50 organic compounds. These compounds were identified most frequently (on 50% or more of the sample days) and occurred at concentrations greater than 10 ng/L on at least one of those days.

For the most part GAC removed the identified substances. The degree of removal and length of effectiveness, however, varied from compound to compound. Some compounds such as tetrachloroethene, 1,2-dichlorobenzene, and hexachloroethane were well adsorbed (85-100%) by GAC over the entire sample period. Other compounds were initially adsorbed (85% to 100%) but desorbed with time such as diisopropyl ether, benzene, and carbon tetrachloride. A few compounds (toluene, ethyl benzene, 1,2-4-trimethylbenzene, and 1,2,3,4-tetramethylbenzene) were adsorbed only to a limited extent by GAC. Concentrations of two compounds (nonanal and decanal) were higher in the effluent than in the influent. It is suspected that this was caused by the compounds either leaching from the contactor liner, a result of laboratory contamination, or bacterial degradation of adsorbed organics.

Operation of GAC contactor A was allowed to continue for about a year to evaluate its adsorbtive capacity for the various compounds listed in Tables 8 and 9. After a certain period of use, the GAC was exhausted for some of the compounds. This effect is especially prevalent in Table 9 where the minus percent removal indicates desorption has occurred.

TABLE 8. PERCENT REMOVAL DATA SUMMARY OF GROB CLSA RESULTS FOR CONTACTOR A, CINCINNATI, OHIO

Compound	Runday				
	1	34	64	113	134
Diisopropylether	a	100	100	100	d
1,1,1-Trichloroethane	e	95	87	94	98
Benzene	a	100	a	100	99
Carbon tetrachloride	100	94	93	100	100
Cyclohexane	h	21	g	100	c
1,2-Dichloropropane	a	100	g	g	g
Trichloroethene	a	98	98	100	100
Methylcyclohexane	d	a	a	100	g
4-Methyl-2-pentanone	a	g	100	100	g
Toluene	38	72	-3	59	100
Hexanal	-100	9	34	e	18
Tetrachloroethene	100	100	98	100	100
Chlorobenzene	a	100	92	100	100
Ethylbenzene	25	c	22	62	99
1,3-and 1,4-Dimethylbenzene	38	51	2	20	98
Styrene	100	100	40	100	100
1,2-Dimethylbenzene	40	58	17	59	99
Isopropylbenzene	37	50	33	67	99
Propylbenzene	33	36	0	62	98
Ethyl-4-methylbenzene	43	48	17	32	98
1,3,5-Trimethylbenzene	33	c	e	e	e
1,2,4-Trimethylbenzene	27	43	11	46	99
Octanal	b	d	-77	39	d
1,4-Dichlorobenzene	100	100	100	100	d
1,2,3-Trimethylbenzene	33	46	100	100	99
1,2-Dichlorobenzene	100	100	99	100	98
1,3-Diethylbenzene	40	d	e	67	99
1,4-Diethylbenzene	d	-100	h	c	e
5-Ethyl-1,3-dimethylbenzene	60	e	0	57	99
Hexachloroethane	100	99	98	100	99
2-Ethyl-4,4-dimethylbenzene	80	50	d	b	e
4-Ethyl-1,2-dimethylbenzene	50	e	20	50	99
Nonanal	-350	-350	-150	-9	-1300
3-Ethyl-1,2-dimethylbenzene	70	e	0	b	99
1,2,3,5-Tetramethylbenzene	-50	55	e	h	99
1,3-Diethyl-5-methylbenzene	50	0	0	100	100
1,2-3,4-Tetramethylbenzene	60	50	50	83	99
Decanal	-150	-680	-120	-17	d
Dodecanal	a	b	h	100	d

TABLE 8. (Cont'd)

Compound	Runday 1	34	64	113	134
2,6-Bis(1,1-dimethylethyl)2,5-cyclohexadiene-1,4-dione	67	e	70	100	e
1,1,3-Trimethyl-3-phenylindan	33	c	-10	h	d
Heptradecane	33	d	-180	e	d
Dibutylphthalate	a	c	c	c	h
Dioctylphthalate	a	a	g	100	h
Hexane	a	a	a	a	a
Methylcyclopentane	a	a	a	a	a

---

[a] Not detected.
[b] Not detected in influent
[c] Not quantified.
[d] Influent not quantified
[e] Effluent not quantified.
[f] Not scanned.
[g] Influent not quantified and effluent not detected.
[h] Influent not detected and effluent not quantified.

Table 9. PERCENT REMOVAL DATA SUMMARY OF GROB CLSA RESULTS FOR CONTACTOR A, RUNDAYS 162 THROUGH 302

Compound	Runday 162	190	218	246	274	302
Diisopropylether	67	-114	f	g	b	g
1,1,1-Trichloroethane	56	70	f	c	-35	d
Benzene	100	100	a	40	- 4	-46
Carbon tetrachloride	100	a	100	e	e	-96
Cyclohexane	90	-46	d	c	c	c
1,2-Dichloropropane	a	100	a	a	h	h
Trichloroethene	100	100	a	100	a	17
Methylcyclohexane	100	d	g	c	g	g
4-Methyl-2-pentanone	88	-166	b	a	g	a
Toluene	90	-83	42	15	-21	-75
Hexanal	63	-15	e	a	0	g
Tetrachloroethene	100	100	100	e	86	92
Chlorobenzene	100	a	a	h	c	g
Ethylbenzene	e	-286	e	c	-3900	65
1,3-and 1,4-Dimethylbenzene	71	-220	33	a	a	a
Styrene	95	h	a	a	e	e

TABLE 9 (Cont'd)

Compound	Runday					
	162	190	218	246	274	302
1,2-Dimethylbenzene	84	-75	e	e	-2000	23
Isopropylbenzene	96	0	b	g	d	c
Propylbenzene	83	-33	a	g	c	c
Ethyl-4-methylbenzene	e	-25	56	100	-43	-350
1,3-5-Trimethylbenzene	c	d	c	e	e	16
1,2,4-Trimethylbenzene	68	0	36	57	-100	-24
Octanal	68	-60	e	h	44	d
1,4-Dichlorobenzene	99	100	100	e	89	86
1,2,3-Trimethylbenzene	80	0	d	e	e	-12
1,2-Dichlorobenzene	99	98	100	100	100	100
1,3-Diethylbenzene	g	h	c	g	c	c
1,4-Diethylbenzene	83	h	c	g	g	c
5-Ethyl-1,3-dimethylbenzene	e	0	d	100	e	e
Hexachloroethane	99	100	100	a	100	100
2-Ethyl-1,4-dimethylbenzene	c	g	d	e	c	e
4-Ethyl-1,2-dimethylbenzene	73	0	a	100	e	-220
Nonanal	54	-80	-23	-48	23	-15
3-Ethyl-1,2-dimethylbenzene	b	b	b	g	c	g
1,2,3,5-Tetramethylbenzene	e	0	d	e	e	0
1,3-Diethyl-5-methylbenzene	a	a	a	a	g	g
1,2,3,4-Tetramethylbenzene	87	a	b	g	e	e
Decanal	65	-76	9	-22	19	-10
Dodecanal	68	-4	-5	h	6	100
2,3-Bis(1,1-dimethylethyl)2,5-cyclohexadiene-1,4-dione	94	100	100	c	100	-52
Pentadecane	h	b	-45	-44	42	75
Diethylphthalate	29	48	g	42	e	35
2,2,4-Trimethylpenta-1,3-dioldisobutyrate	65	100	a	a	91	-2
2,5-Bis(1,1-dimethylproply)2,5-cyclohexadiene-1,4-dione	76	a	c	-81	c	83
1,1,3-Trimethyl-3-phenylindan	e	61	-210	21	84	g
Heptadecane	26	12	-73	57	21	14
Dibutylphthalate	c	c	a	h	80	c
Dioctylphthalate	h	a	a	a	a	a
Hexane	a	-54	f	a	-12	100
Methylcyclopentane	g	-6	f	e	41	c

---

[a] Not detected.

[b] Not detected in influent.

[c] Not quantified.

[d] Influent not quantified.

[e] Effluent not quantified.

[f] Not scanned.

[g] Influent not quantified and effluent not detected.

[h] Influent not detected and effluent not quantified.

The use of TOC as the GAC performance parameter was chosen because of the variability of occurrence of specific organics at low concentrations (ng/L level) and the impossibility of daily monitoring for all organics present in the water. Generally, TOC analysis of the GAC contactor sampling points provided a typical breakthrough curve with increased carbon depth providing lower TOC concentrations for a longer time period. Figure 20 shows a typical example where a TOC influent concentration of 2.0-2.5 mg/L was reduced to below 1.0 mg/L up to about 150 days of operation at an EBCT of 15.2 minutes.

Huntington, West Virginia

In Huntington, West Virginia and Beaver Falls, Pennsylvania, GAC was an intergal part of the treatment scheme for taste and odor control. The adsorptive capacity of virgin GAC in the filtration/adsorption mode was investigated at both utilities. At the time of these studies only a few specific organics, other than the trihalomethanes and their precursors, were detected in the ug/L range.

Most of the purgeable and base-neutral extractable halocarbons were detected infrequently and when detected were typically at or below 0.2 ug/L. Therefore, evaluation of the GAC adsorptive capacity for these compounds was difficult. There were, however, some organic compounds present sporadically in Huntington's water at higher concentrations.

Carbon tetrachloride occurred frequently. Virgin GAC was an effective barrier when high influent concentrations occurred at week ten of operation (13 ug/L in GAC influent and 0.4 ug/L in GAC effluent).

Chlorobenzene concentrations in the ug/L range were detected infrequently in the GAC influent. When detected, concentrations ranged up to 1.0 ug/L (6th week of operation). During the 35th week of operation, the influent concentration was 0.5 ug/L and was not detected in the effluent. In 10 out of 15 sampling times 1,4-dichlorobenzene was detected in the GAC influent at a concentration that ranged from 0.1 to 1.4 ug/L. At week 22 of operation the highest GAC influent concentration of 1.4 ug/L was effectively removed with none detected in the GAC effluent. Occasionally, base-neutral extractable halocarbons were detected. Concentrations in GAC influent waters were low (< 1.0 ug/L) with no concentrations detected in the GAC effluent.

Beaver Falls, Pennsylvania

Occasionally, carbon tetrachloride was detected in the treated water. Its presence was suspected to be a result of a contaminated chlorine supply. When detected, concentrations were typically below 0.2 ug/L but enough data were not available to evaluate the effectiveness of GAC adsorption. Also found occasionally in the GAC influent (plant settled water) was 1,4-dihlorobenzene at concentrations ranging from 0.1 to 0.3 ug/L. Again, not enough data were available to evaluate GAC adsorption efficiency.

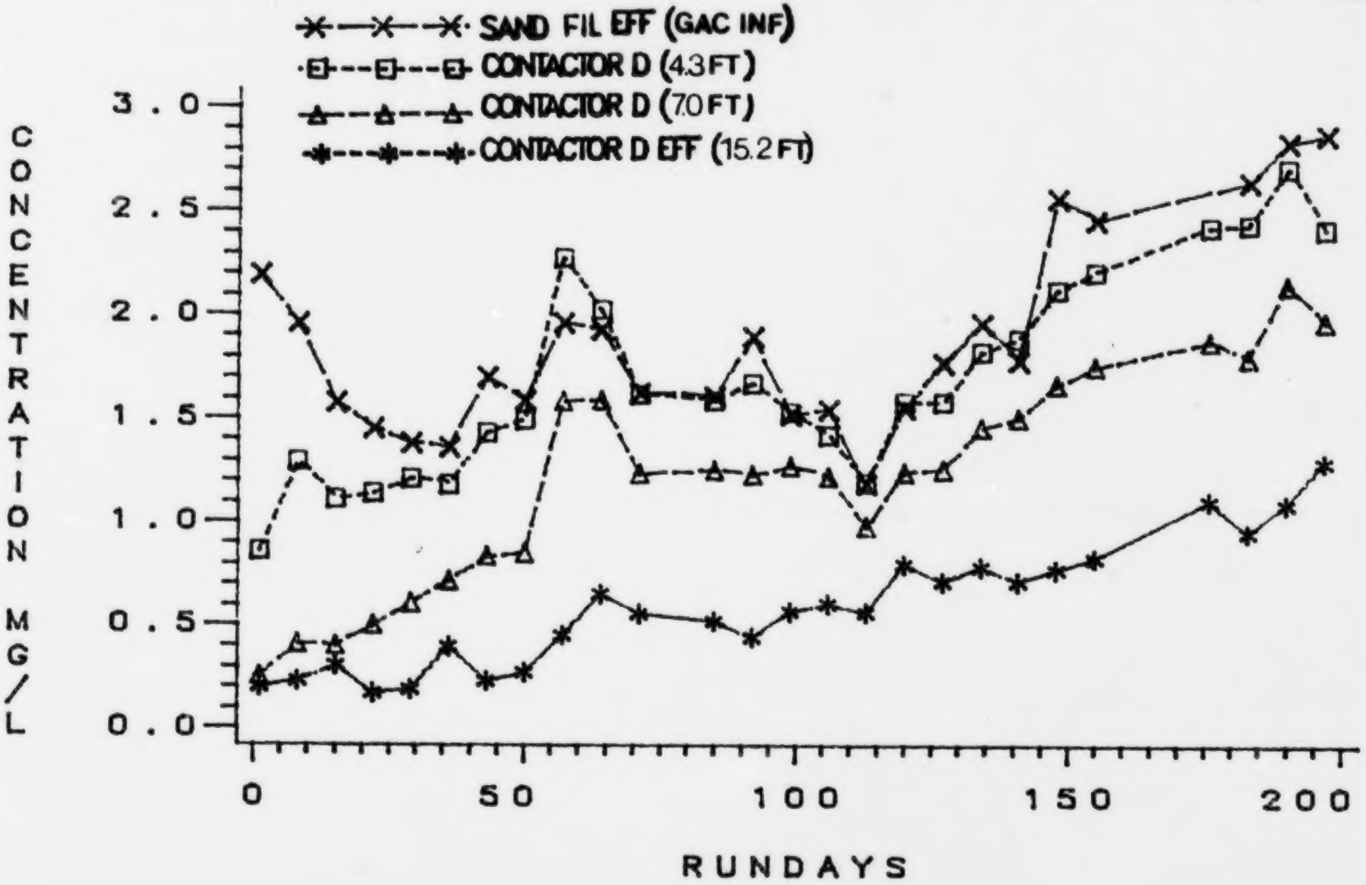


FIGURE 20. TOTAL ORGANIC CARBON (TOC) BREAKTHROUGH CURVES FOR CONTACTOR D, CINCINNATI, OHIO

Unidentified base-neutral extractable halocarbons were detected periodically in the finished water but rarely in the raw water. When detected, their concentrations ranged from 0.1 to 1.2 ug/L. Some adsorption was noted during the first four months of operation but after that time the concentration of the GAC effluents was similar to the influent.

Evansville, Indiana

During this project, only the general parameter (TOC) was detected continuously with most of the other specific organics detected sporadically at the detection limit of the instrumentation used.

The applied TOC concentration to the GAC contactors was between 1.6 and 3.0 mg/L with the lowest concentrations seen during the months of March-May. The virgin GAC effluent, as evaluated by the percent TOC removed, showed that at the beginning of each run this percent was about 80 for two out of three runs and by day 63 steady-state conditions had occurred for all runs (Figure 21).

Occasionally, tetrachloroethylene was detected both in the raw and finished water with concentrations decreasing during treatment. Average instantaneous raw water concentrations ranged from 0.1 to 0.4 ug/L. GAC effluent concentrations were typically less than 0.1 ug/L.

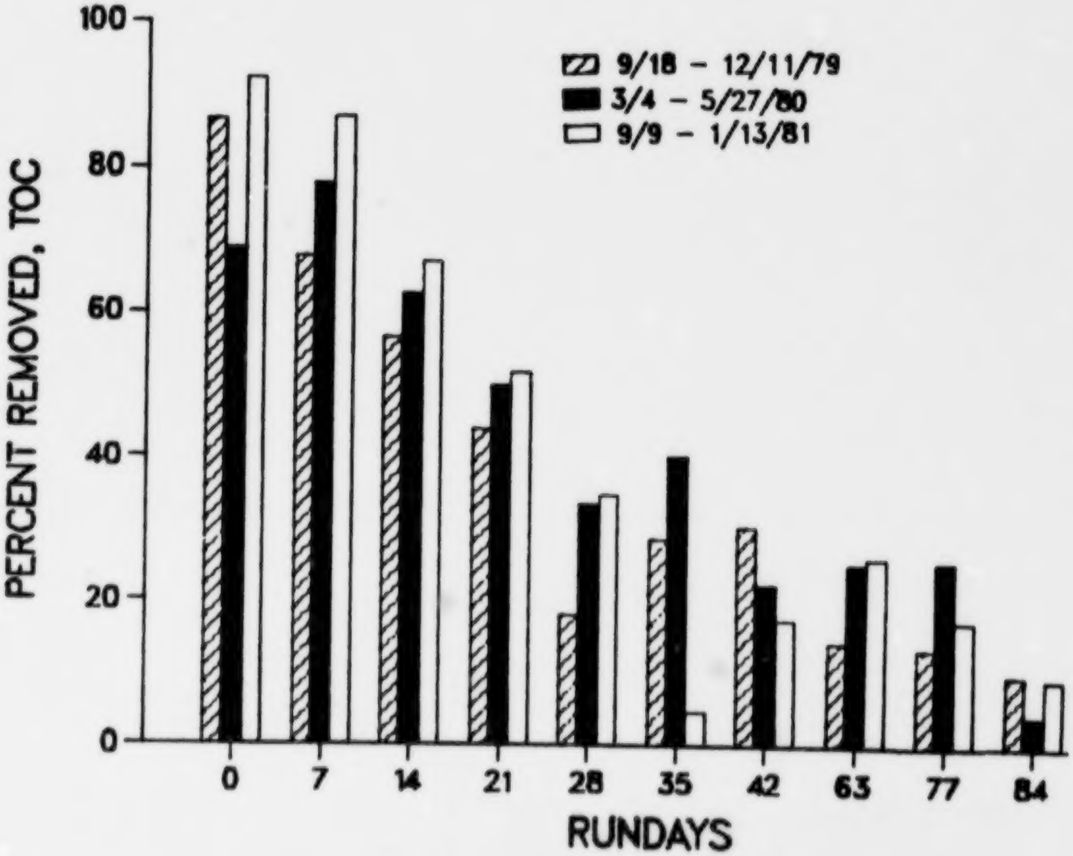
Manchester, New Hampshire

Because of the pristine nature of the source water (Lake Massabesic) no specific organics other than the THM constituents were detected at Manchester. TOC removal by GAC adsorption proceeded according to the typical break-through curve. About 80 percent removal was accomplished at start-up and after approximately 80 days of operation steady state removal conditions were reached at around 30 percent (Figure 22). Influent TOC concentrations applied to the GAC ranged from 1.8 to 2.8 mg/L with most data points in the 2.5 mg/L area.

Miami, Florida

Several halogenated organics were detected in the Miami raw water as shown in Table 10. In most cases the concentration of these organics was reduced during treatment (Table 11). There were some, however, that did increase in concentration such as the summation of 1,1,1-trichloroethane, 1,2-dichloroethane, and carbon tetrachloride. The combined average concentration of these three increased more than any of the other halogenated compounds detected (77 percent) indicating that one or all of these compounds was a contaminant added or produced during treatment. Carbon tetrachloride is suspect. Nonetheless, after 24.8 minutes EBCT, no breakthrough was seen after 122 days of GAC operation.

The halogenated organic compound occurring in highest concentration was cis 1,2-dichloroethene which had a raw water average of 25.6 ug/L. The other compounds were present at much lower concentrations. All of these



BED VOLUME = 150 X RUNDAY

FIGURE 21. PERCENT TOC REMOVED THROUGH VIRGIN GAC, EVANSVILLE, INDIANA

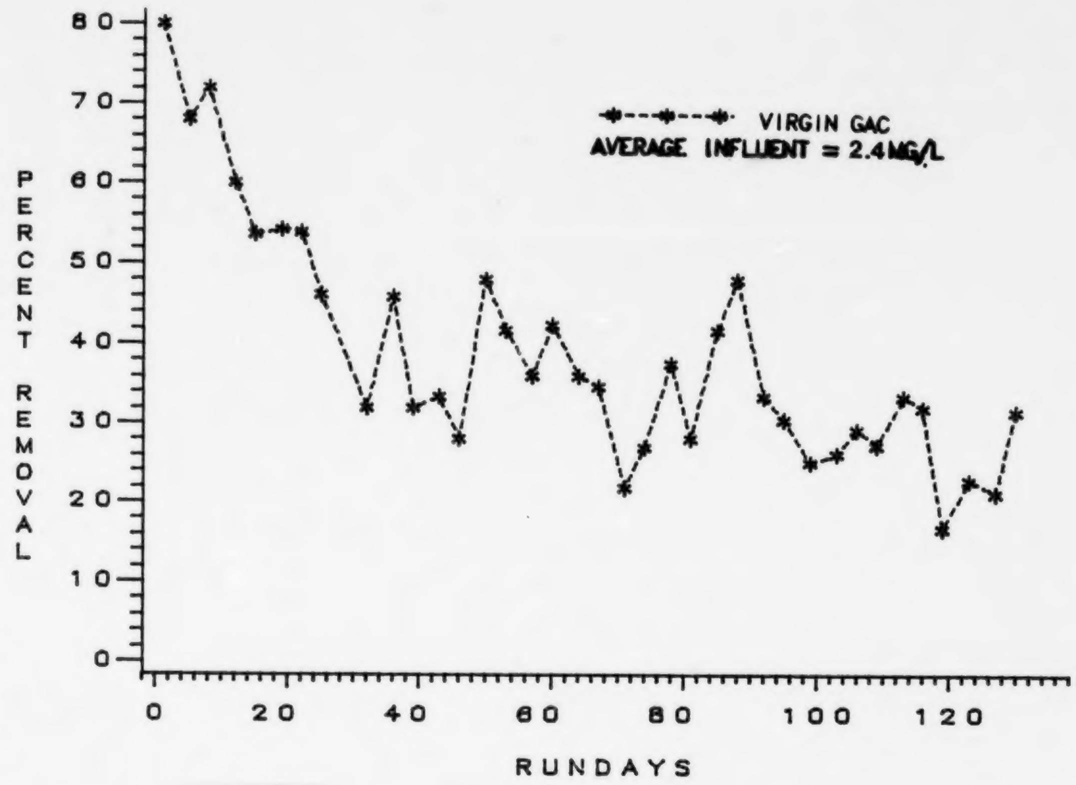


FIGURE 22. PERCENT TOC REMOVAL, MANCHESTER, NEW HAMPSHIRE

organics were removed by virgin GAC for varying periods of time as shown in Table 12.

TABLE 10. AVERAGE CONCENTRATION OF SPECIFIC HALOGENATED ORGANICS IN RAW WATER, MIAMI, FLORIDA

	Average concentration in ug/L Raw Water		
Chemical Name	ED1R	ED3	ED4
Vinyl Chloride	0.8	6.9	12.8
Methylene Chloride	0.1	0.1	0.5
Trans 1,2-Dichloroethene	1.3	2.0	1.5
1,1-Dichloroethane	0.3	0.6	0.6
Cis 1,2-Dichloroethene	29.0	26.9	25.6
1,1,1-Trichloroethane			
1,2-Dichloroethane	0.1(1)	0.2(1)	0.1(1)
Carbon Tetrachloride			
Trichloroethylene	0.1	0.4	0.3
Tetrachloroethylene	0.1	N	N
Chlorobenzene	0.2	1.3	1.1
p-chlorotoluene	0.1	0.2	N
m-dichlorobenzene			
p-dichlorobenzene	1.1(2)	1.0(2)	0.7(2)
o-dichlorobenzene			

N - Nil
ED1R - Repeat of study 1 (Jan. 18 - May 20, 1977)
ED3 - Study 3 (Aug. 26 - Oct. 18, 1977)
ED4 - Study 4 (Nov. 1, 1977 - Mar. 3, 1978)

(1) Values were summed because the three peaks overlapped making separate analysis impractical with available instrumentation.

(2) Summed becaused available chromatographic techniques could not separate isomers.

TABLE 11. AVERAGE CONCENTRATION OF SPECIFIC HALOGENATED ORGANICS IN FINISHED WATER, MIAMI, FLORIDA

	Average concentration in ug/L		
	Finished Water		
Chemical Name	ED1R	ED3	ED4
Vinyl Chloride	0.6	5.7	8.4
Methylene Chloride	ND	ND	ND
Trans 1,2-Dichloroethene	0.2	1.0	0.8
1,1-Dichloroethane	0.2	0.3	0.4
Cis 1,2-Dichloroethene	17.2	18.3	19.9
1,1,1-Trichloroethane			
1,2-Dichloroethane	0.7(1)	5.3(1)	7.7(1)
Carbon Tetrachloride			
Trichloroethylene	0.2	0.1	0.7
Tetrachloroethylene	N	N	N
Chlorobenzene	0.1	0.8	0.9
p-chlorotoluene	N	.2	.1
m-dichlorobenzene			
p-dichlorobenzene	0.6(2)	0.3(2)	0.4(2)
o-dichlorobenzene			

N - Nil
ND - Not determined
ED1R - Repeat of study 1 (Jan. 18 - May 20, 1977)
ED3 - Study 3 (Aug. 26 - Oct. 18, 1977)
ED4 - Study 4 (Nov. 1, 1977 - Mar. 3, 1978)

(1) Values were summed because the three peaks overlapped making separate analysis impractical with available instrumentation.

(2) Summed because available chromatographic techniques could not separate isomers.

TABLE 12. DURATION OF REMOVAL BY GAC FOR HALOGENATED ORGANICS DETECTED IN MIAMI, FLORIDA WATER

Study	EBCT, min.	Avg. Inf. ug/L	Column Breakthrough, Days	Column Saturation, Days
ED1R				
cis 1,2-dichloroethene	6.2	29	16	73
trans 1,2-dichloroethene	6.2	1.3	66	142
1,1-dichloroethane	6.2	0.3	21	94
1,1,1-trichloroethane				
1,2-dichloroethane	6.2	0.1	21	98
carbon tetrachloride				
trichloroethylene	6.2	0.1	77	>122
chlorobenzene	6.2	0.2	>122	>122
ED3				
cis 1,2-dichloroethene	6.2	18.3	18	53
vinyl chloride	6.2	5.7	21	>53
trans 1,2-dichloroethene	6.2	1.0	>53	>53
1,1-dichloroethane	6.2	0.3	16	21
1,1,1-trichloroethane				
1,2-dichloroethane	6.2	5.3	28	58
carbon tetrachloride				
trichloroethylene	6.2	0.1	(1)	(1)
chlorobenzene	6.2	0.8	>53	>53

TABLE 12. (Cont'd)

Study	EBCT, min.	Avg. Inf. ug/L	Column Breakthrough, Days	Column Saturation, Days
ED4				
cis 1,2-dichloroethene	24.8	19.9	>122	>122
vinyl chloride	24.8	8.4	35	87
trans 1,2-dichloroethene	24.8	0.8	>122	>122
1,1-dichloroethane	24.8	0.4	77	87
1,1,1-trichloroethane				
1,2-dichloroethane	24.8	7.7	>122	>122
carbon tetrachloride				
trichloroethylene	24.8	0.7	(1)	(1)
chlorobenzene	24.8	0.9	>122	>122

---

(1)Detected concentrations were sporadic

Passaic Valley, Little Falls, New Jersey

At a short EBCT of 8 minutes, effective performance of the GACs used at Passaic Valley was limited. Both TOC and TOX reached a removal plateau after approximately 9 weeks of operation at 30 and 40 percent, respectively. Although a total of 42 organic parameters were analyzed including chlorinated pesticides and volatile halogenated solvents only a few were detected, at the ug/L level, in the influent applied to the GAC with any consistency.

These included carbon tetrachloride and tetrachloroethylene. Out of 32 observations that included 102 days of operation, carbon tetrachloride was seen in the GAC influent 8 times (during days 46-89) at a concentration range of 0.05 to 0.31 ug/L. Removal of the carbon tetrachloride by the GACs was somewhat erratic with the GAC effluent concentration sometimes higher than the influent (Table 13).

The other volatile organic (tetrachloroethylene) was also detected sporadically. Its removal was consistent among the three GACs evaluated and only on operational day 81 was the effluent concentration higher than the influent concentration (Table 14).

TABLE 13. CARBON TETRACHLORIDE GAC INFLUENT AND EFFLUENT CONCENTRATIONS, PASSAIC VALLEY, NEW JERSEY

		GAC Effluent		
Operation Day Observed(1)	GAC Influent (ug/L)	HD-1030® (ug/L)	WV-W® (ug/L)	F-400® (ug/L)
46	0.24	0.32	0.43	0.23
53	0.18	0.31	0.31	0.30
60	0.31	0.25	0.24	0.25
67	0.15	0.03	0.02	0.03
75	0.16	0.14	0.14	0.16
81	0.07	0.16	0.17	0.11
88	0.11	0.08	0.06	0.05
89	0.05	–	0.04	0.06
Avg.	0.16	0.18	0.18	0.15

---

(1) Days of detectable concentrations

TABLE 14. TETRACHLOROETHYLENE GAC INFLUENT AND EFFLUENT CONCENTRATIONS, PASSAIC VALLEY, NEW JERSEY

		GAC Effluent		
Operation Day Observed(1)	GAC Influent (ug/L)	HD-1030® (ug/L)	WV-W® (ug/L)	F-400® (ug/L)
46	0.66	0.06	0.12	0.11
53	0.73	0.14	0.25	0.19
67	0.58	0.11	0.07	0.08
75	1.16	0.86	0.88	0.93
81	0.66	0.88	0.97	0.64
88	0.28	0.06	0.03	0.03
89	0.05	–	0.03	0.04
Avg.	0.59	0.35	0.33	0.29

---

(1) Days of detectable concentrations

Thornton, Colorado

Except for the four major trihalomethanes, no other specific organics were evaluated. The surrogate parameters of TOC and TOX were used to determine the effectiveness of GAC. As described previously, various treatment modes were used prior to GAC adsorption. The GAC was used both in the post-sand filtration adsorption and combined filtration/adsorption schemes. The EBCT was 20 min. for each of these adsorption schemes.

Table 15 shows the average concentration of TOC for four treatment modes. As indicated in this table, various conventional treatment schemes did reduce the raw water TOC concentration (avg. raw water range 4.7 - 5.7 mg/L and pilot plant effluent 4.1 - 4.6 mg/L). The GAC further reduced the TOC concentration. The range for the filter adsorber effluent for the four modes was 0.6 - 1.1 mg/L and for the adsorber effluent was 0.8 - 2.1 mg/L.

TOX precursor concentrations were reduced during conventional treatment. The degree of reduction was dependent on the pre-disinfectant scheme used. Also, the pre-disinfectant scheme did impact the instantaneous TOX concentration in the pilot plant filter effluent (Table 16). Although average concentrations can be misleading, those presented in Table 16 typify what was seen during treatment. During the longer runs (6 months), the term TOX adsorber effluent was higher than the filter adsorber effluent indicating that adsorbed material on the mixed media filter or GAC was contributing to the TOX formation potential. An example of TOX reduction through GAC is shown in Figure 23 for mode I. In this mode the 5-day terminal TOX was effectively removed by GAC through 160 days of operation.

TABLE 15. AVERAGE CONCENTRATIONS FOR TOC DURING THORNTON, COLORADO PROJECT

	TOC, mg/L			
MODE	Raw Water	Pilot Plant Filter Effluent	Filter/Adsorber Effluent	Adsorber Effluent
1 (6 months)	5.1	4.1	0.9	1.3
2 (2 months)	5.7	4.5	0.9	1.2
3 (3 months)	5.5	4.6	0.6	0.8
4 (6 months)	4.7	4.3	1.1	2.1

TABLE 16. AVERAGE CONCENTRATIONS FOR TOX DURING THORNTON, COLORADO PROJECT

	Inst/Term(1) TOX, ug/L			
MODE	Raw Water	Pilot Plant Filter Effluent	Filter/Adsorber Effluent	Adsorber Effluent
1 (6 months)	92/597	464/475	92/171	128/266
2 (2 months)	34/121(2)	187/395	29/61	21/30
3 (3 months)	30/452	142/404	13/32	20/22
4 (6 months)	41/315	75/164	42/78	23/151

---

(1) Stored 5-days, pH 8.0, Temp - ambient

(2) Cl_2 residual not maintained during 5-day storage period.

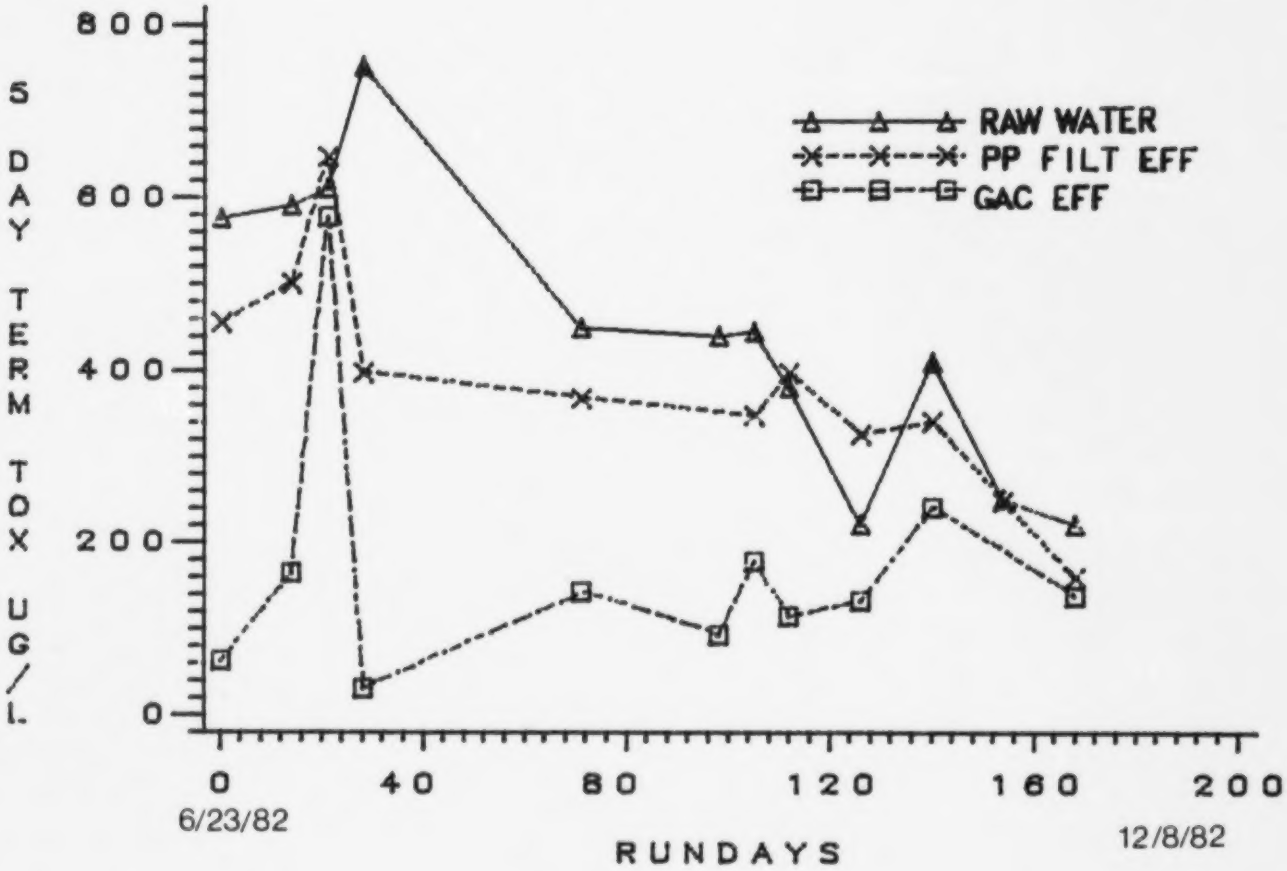


FIGURE 23. TOX REDUCTION BY GAC – THORNTON, CO.

SECTION V

PERFORMANCE COMPARISON OF FIELD-SCALE PROJECTS

Adsorber vs Filter-Adsorber

In three field-scale locations (Cincinnati, Jefferson Parish, and Thornton) both the adsorber and filter-adsorber mode of operation were used. The adsorber mode consisted of sand filtration prior to GAC adsorption and the filter-adsorber mode consisted of applying coagulated and settled effluent directly to the GAC. At Cincinnati, the filter adsorber (sand replacement) determined the EBCT that was used for comparison (7.5 vs 7.2 minutes for sampling point on contactor). The actual TOC concentrations for these contact times are shown in Figure 24. When variables such as flow rate, influent concentration, and amount of GAC are considered as shown in Figure 25, the apparent slightly better performance of the adsorber can probably be attributed to a slightly lower influent concentration.

At Jefferson Parish, a comparison was made of the adsorber and filter adsorber for all four phases of the project. As with any full-scale project, maintenance of exact operating conditions for comparative purposes is difficult. There were, however, two phases (IIB and III) whereby TOC influent concentrations and EBCTs were similar enough for comparison of the adsorber and filter adsorber performance. Phase IIB showed better performance for the adsorber but its EBCT was 3.3 min longer than the filter adsorber (17.0 vs. 13.7 minutes). The TOC performance of the adsorber and filter adsorber was most comparable in Phase III. A slight advantage was seen with the filter adsorber and was probably due to a 4.4 minute longer EBCT (23.2 vs. 18.8 minutes). Figure 26 shows the percent TOC removal for those two phases.

Consistent detection of a few specific organics also showed in Phase IIB and III that the adsorber and filter adsorber performed essentially the same. For instance, 1,2-dichloroethane and trichloroethylene followed each other except for an occasional discrepancy. This closeness of performance occurred even during desorption of the 1,2-dichloroethane (Figures 27 and 28).

By using the pilot plant at Thornton, Colorado for evaluation of the adsorber and filter adsorber GAC scheme, a consistent EBCT could be maintained for both. With an EBCT of 20 minutes for each adsorption system, one can see from the average concentrations presented in Figure 29 that for all modes evaluated, the filter adsorber effluent concentration for TOC was lower than for the adsorber effluent. This occurred although the average applied concentration was similar.

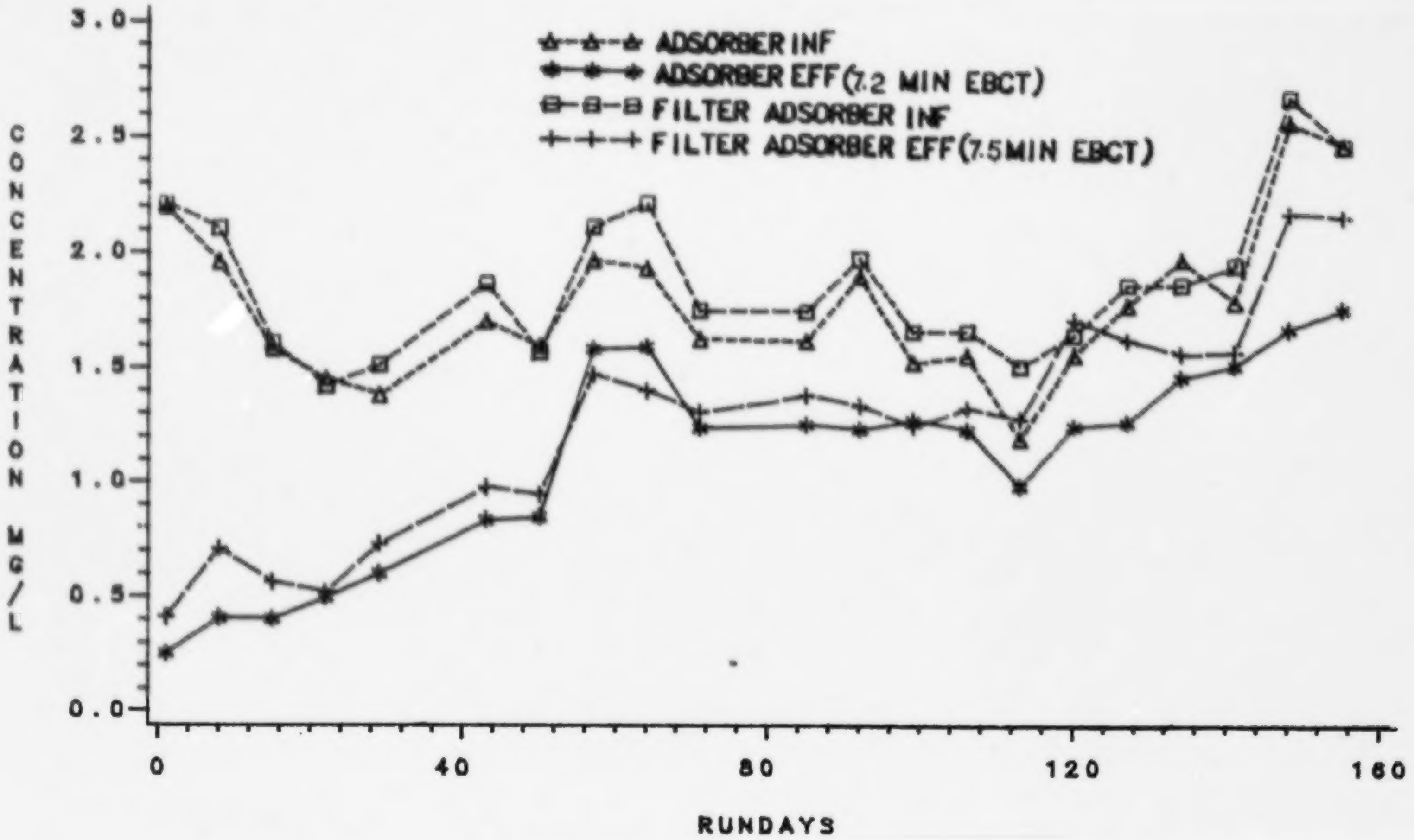


FIGURE 24. COMPARISON OF ADSORBER AND FILTER ADSORBER PERFORMANCE FOR TOC – CINCINNATI, OHIO

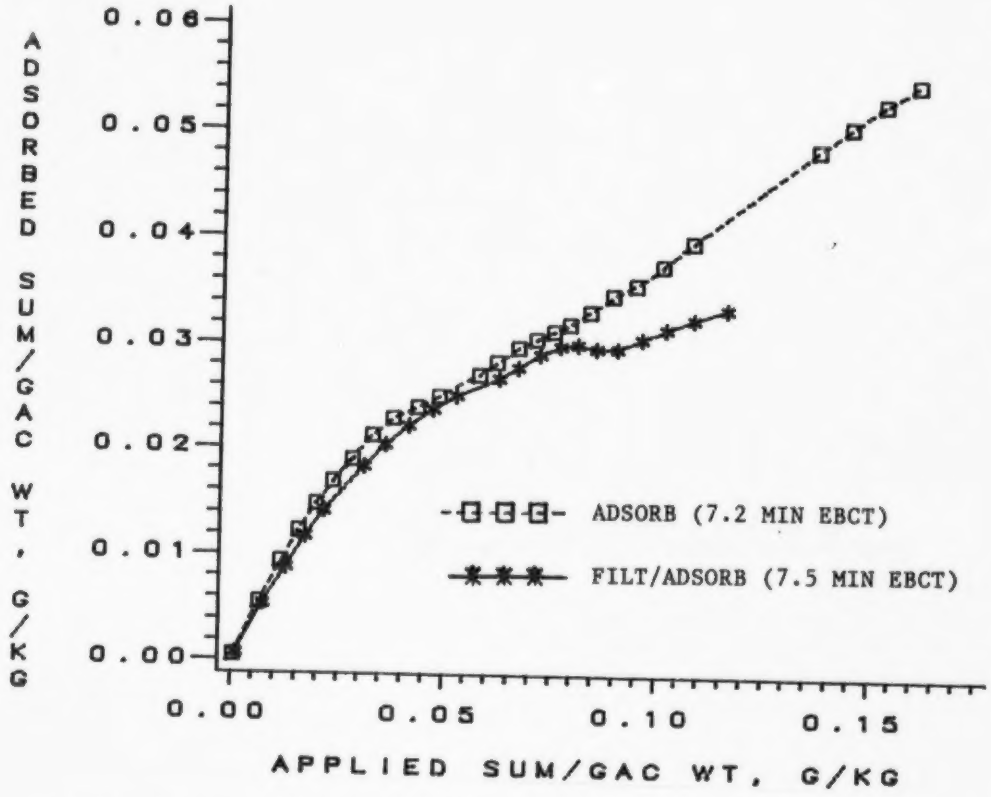


FIGURE 25. TOC LOADING ON VIRGIN GAC FOR ADSORBER AND FILTER ADSORBER AT COMPARABLE EBCTs — CINCINNATI, OHIO

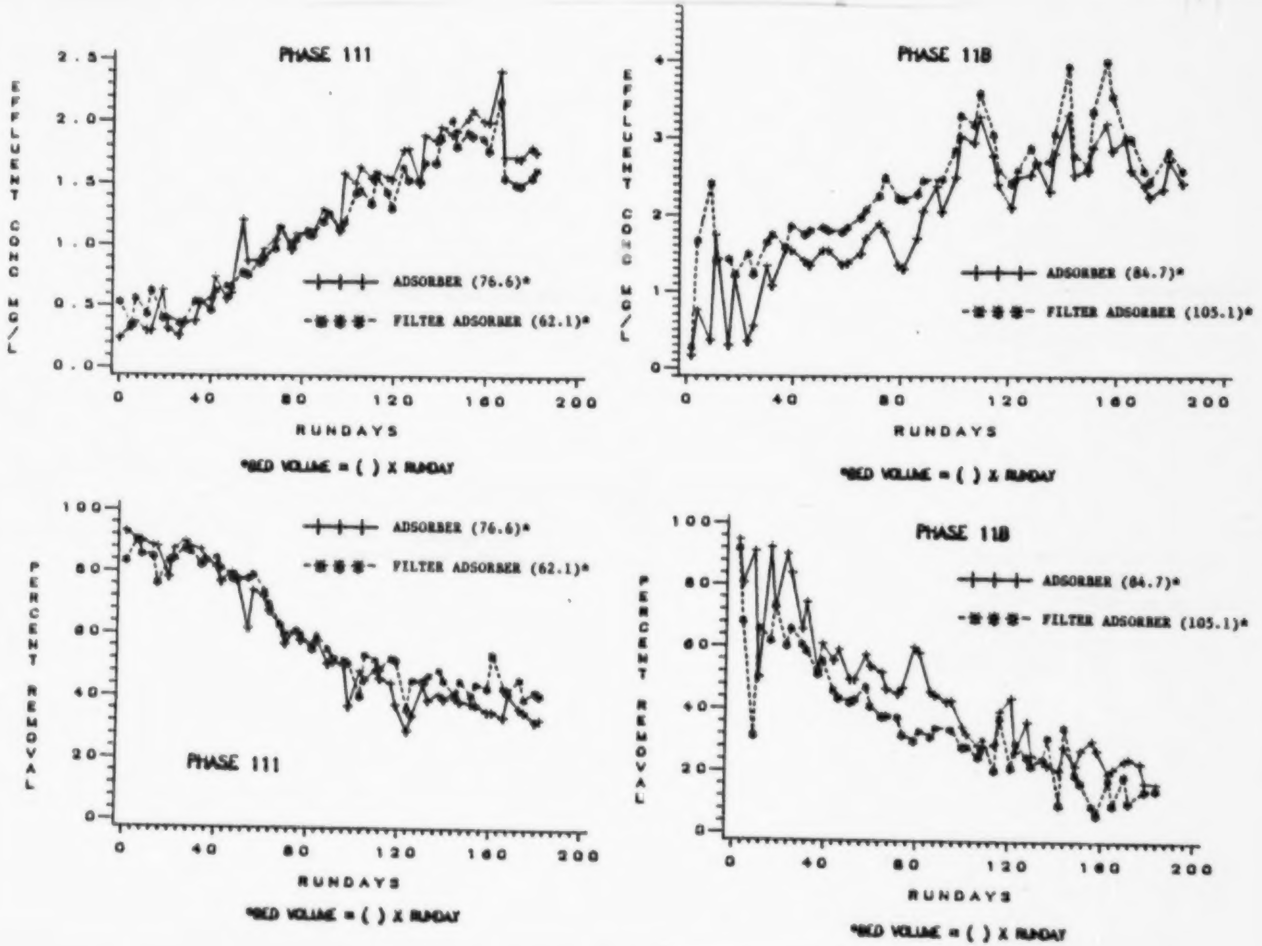


FIGURE 26. TOC REMOVAL FOR ADSORBER AND FILTER ADSORBER AT JEFFERSON PARISH, LA.

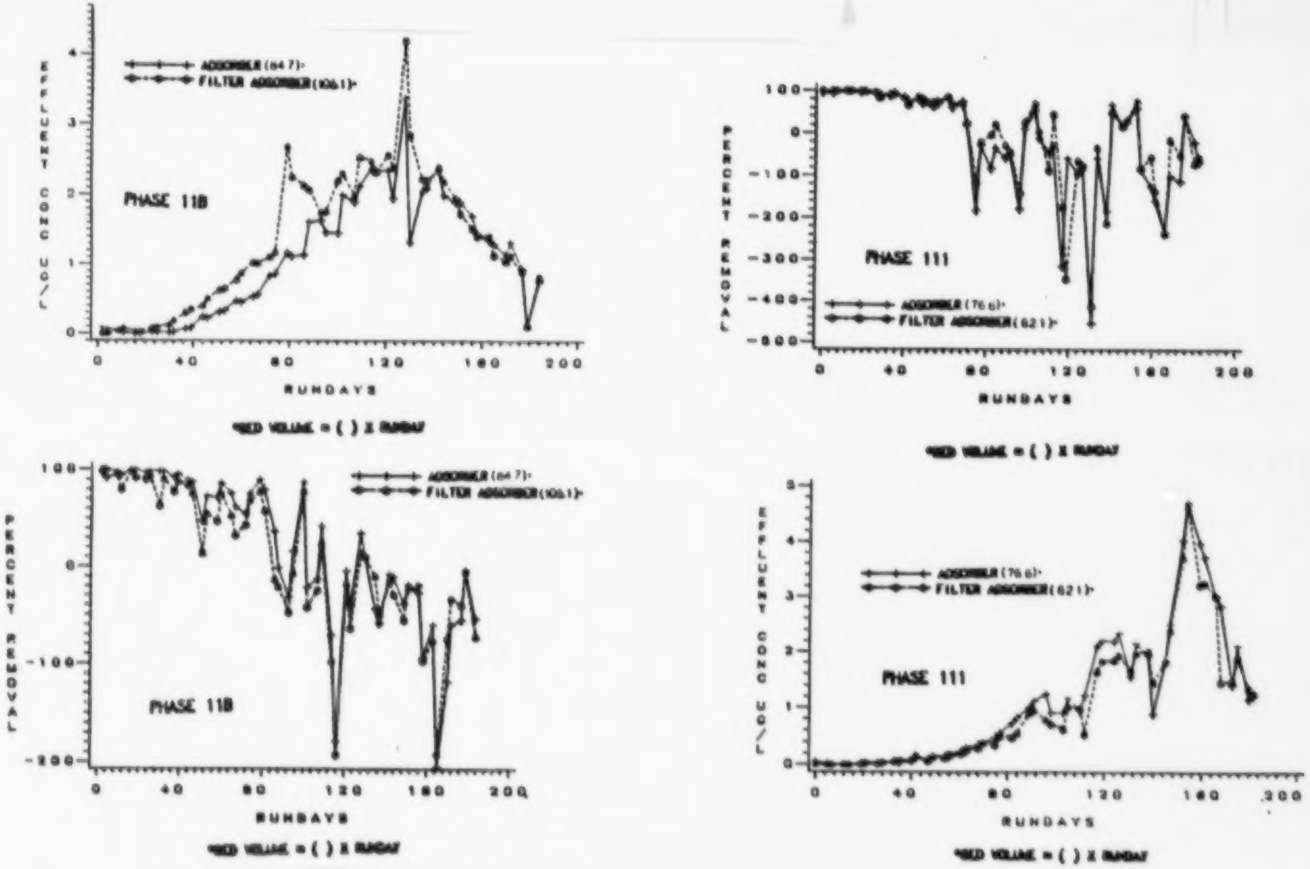


FIGURE 27. COMPARISON OF ADSORBER AND FILTER ADSORBER PERFORMANCE FOR 1,2 DICHLOROETHANE AT JEFFERSON PARISH, LA.

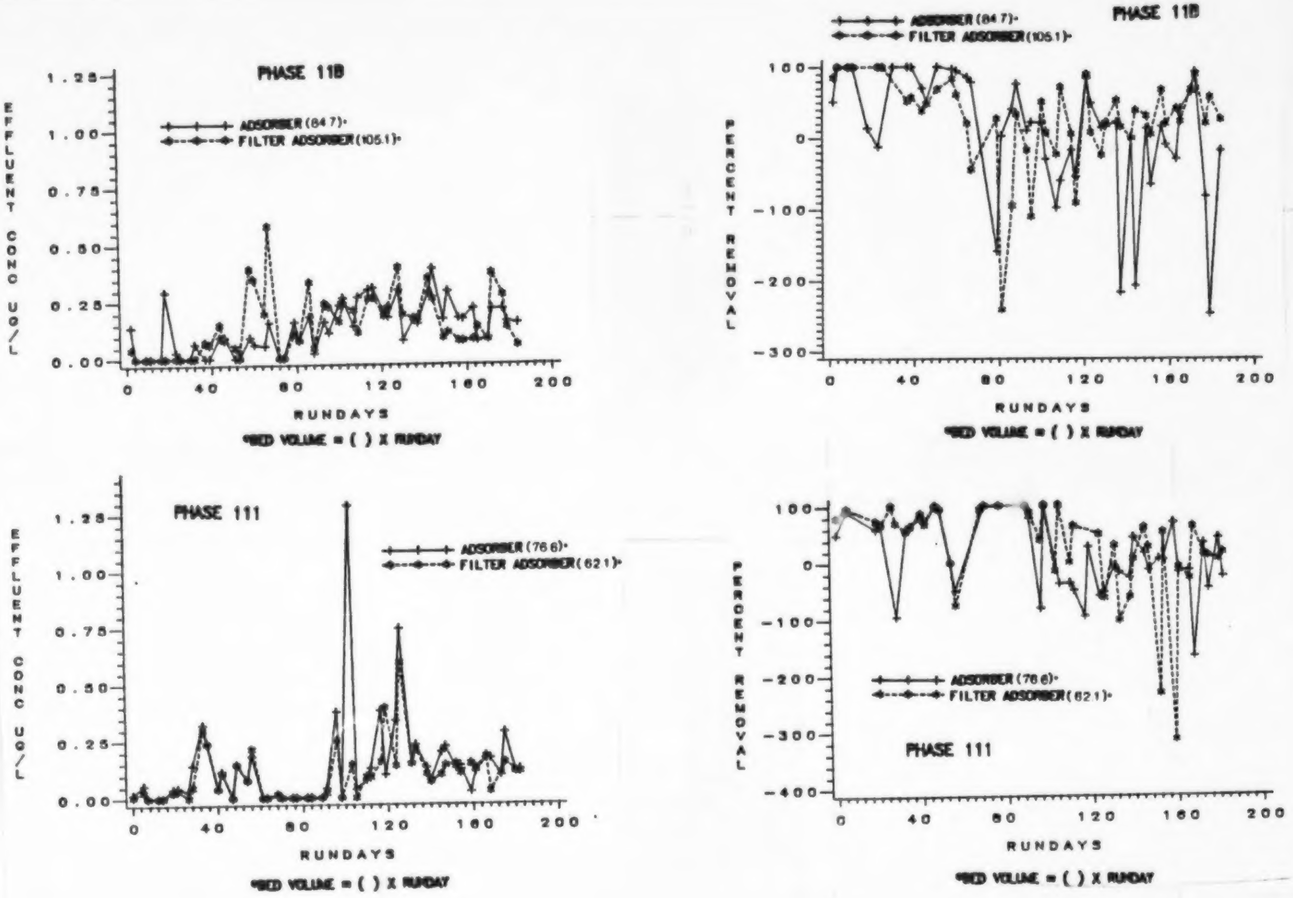


FIGURE 28. COMPARISON OF ADSORBER AND FILTER ADSORBER PERFORMANCE FOR TRICHLOROETHYLENE AT JEFFERSON PARISH, LA.

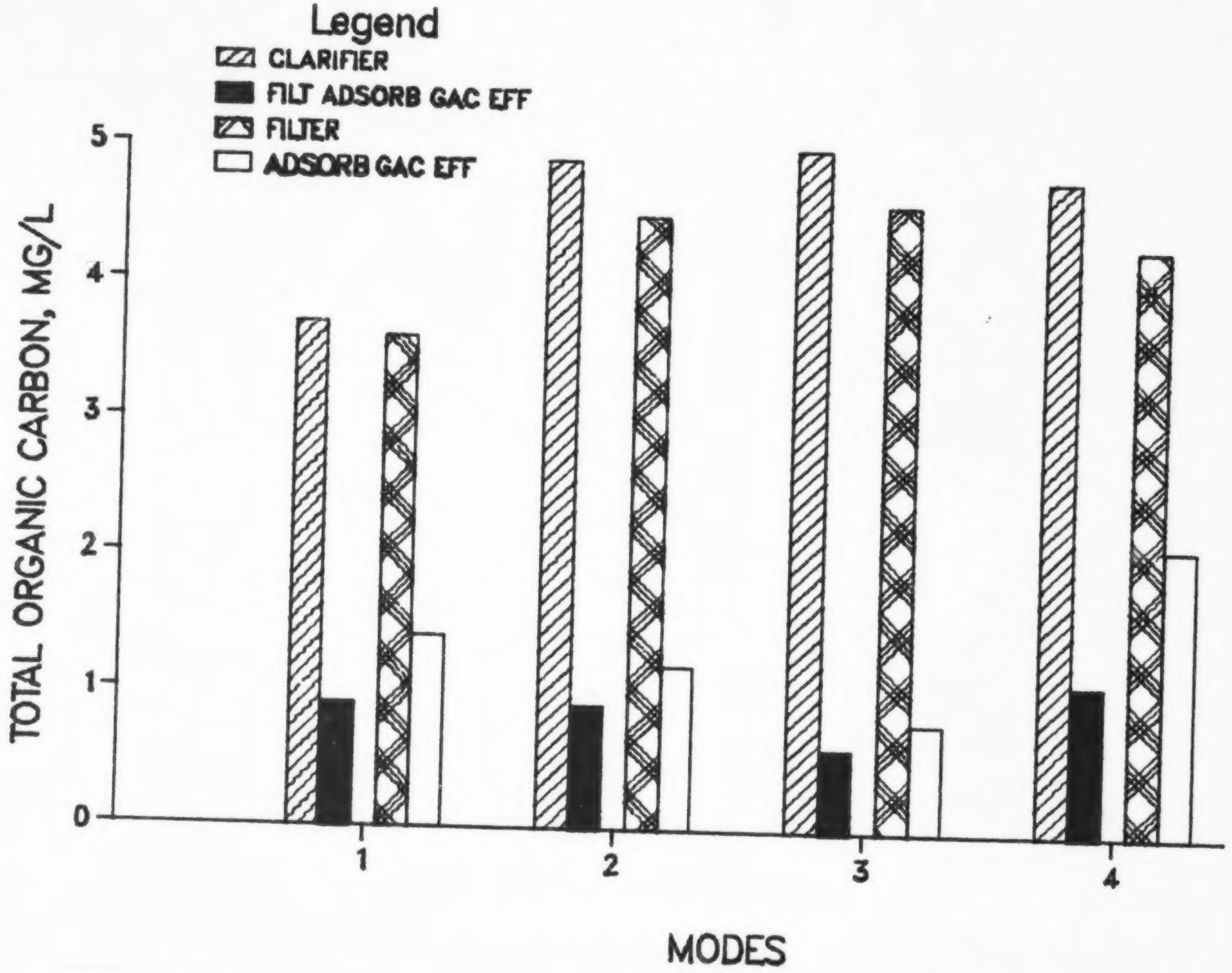


FIGURE 29. AVERAGE GAC PERFORMANCE DURING TREATMENT MODES—THORNTON, CO.

For terminal TOX as shown in Figure 30, longer runs (6 months in this case for modes 1 and 4) may be accomplished by applying clarifier effluent directly to GAC for removal of TOX precursors as indicated by the lower terminal values. The average instantaneous TOX (Figure 31) in Mode 4 adsorber effluent was lower than the filter adsorber effluent. This probably occurred because chloramines were produced in the treatment process for disinfection and only partially reacted with the TOX precursors.

Pilot vs Full-Scale GAC Systems

The ability to predict full-scale GAC performance from pilot systems provides utilities with an economical screening mechanism to utilize before making decisions relative to GAC use. In Cincinnati, the 7.6 cm (3 in.) diameter by 76.2 cm (30 in.) deep columns had approximately the same hydraulic loading applied as in the full-scale systems as shown in Table 17.

TABLE 17. HYDRAULIC LOADING RATE OF PILOT AND FULL SCALE SYSTEMS - CINCINNATI, OHIO

GAC Filter System	Phase	Hydraulic Loading Adsorber			Hydraulic Loading Filter/Adsorber		
		(m/hr)	(gpm/sq ft)	EBCT	(m/hr)	(gpm/sq ft)	EBCT
Pilot	3-0	18.2	7.6	14.8	6.0	2.5	7.6
Full-Scale		17.8	7.4	15.3	6.0	2.5	7.5
Pilot	3-1	17.0	7.1	15.8	6.0	2.5	7.6
Full-Scale		17.8	7.4	15.3	6.0	2.5	7.5
Pilot	3-2	16.6	6.9	16.4	5.8	2.4	7.8
Full-Scale		17.8	7.4	15.3	6.0	2.5	7.5

In phase 3-0 and 3-1 (virgin and once reactivated GAC, respectively) the pilot system predicted the full-scale adsorber performance within 10 percent for up to 100 days in most cases. In phase 3-2 (twice reactivated GAC) the pilot system prediction of full-scale adsorber performance was within 5 percent for 60 days of operation (Figure 32). For all phase observations, the full-scale adsorber data showed a more efficient removal of TOC than the corresponding pilot column. The performance differences in the two systems have not been completely explained but maintaining consistent and accurate flows is suspect.

Essentially identical TOC removals for the pilot and full-scale filter adsorber systems were seen in Phase 3-0 (Figure 33). In the other two runs (3-1 and 3-2), the pilot predictor in most cases removed more TOC than the full-scale sand replacement filter.

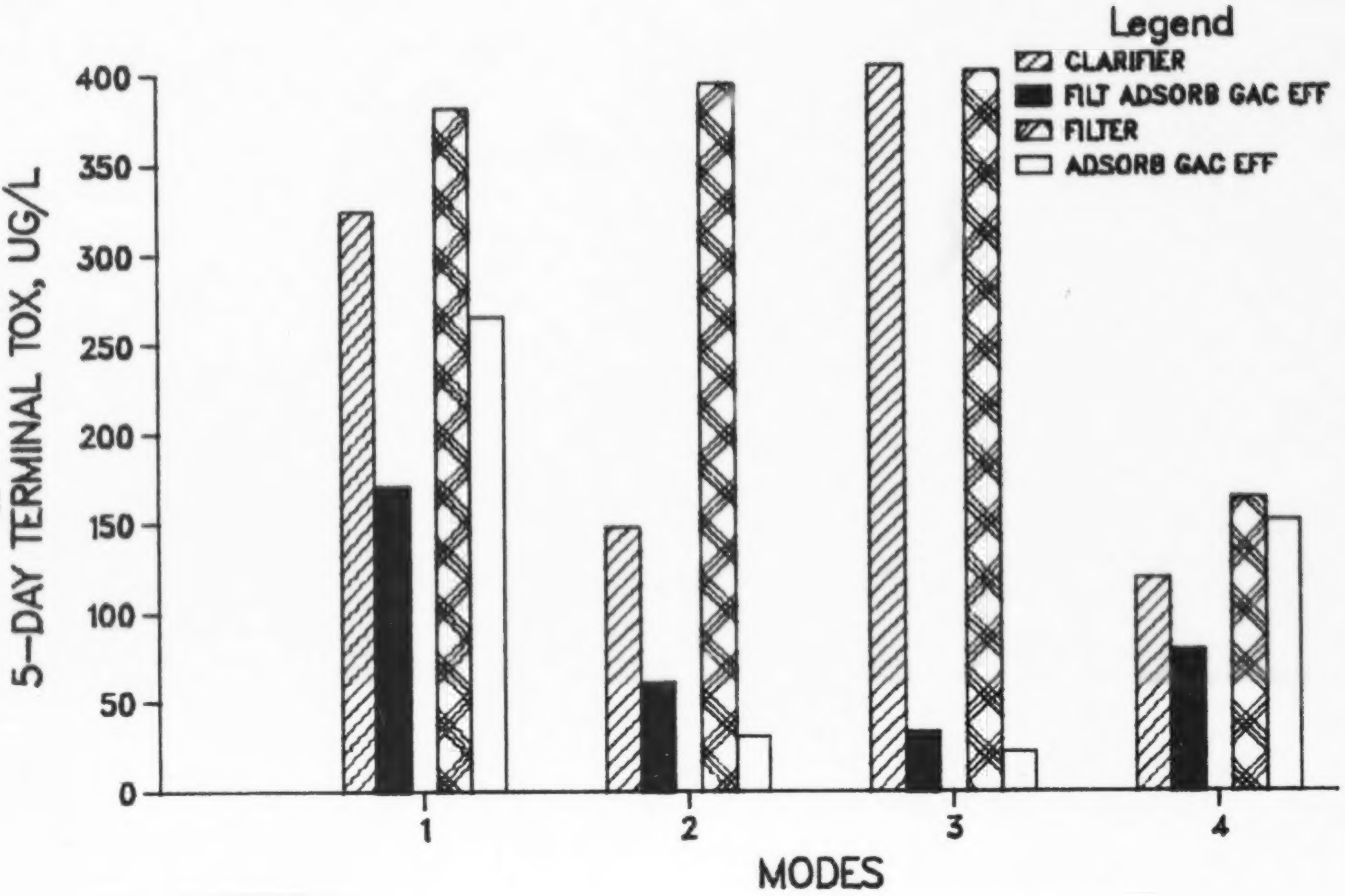


FIGURE 30. AVERAGE GAC PERFORMANCE DURING TREATMENT MODES—THORNTON, CO.

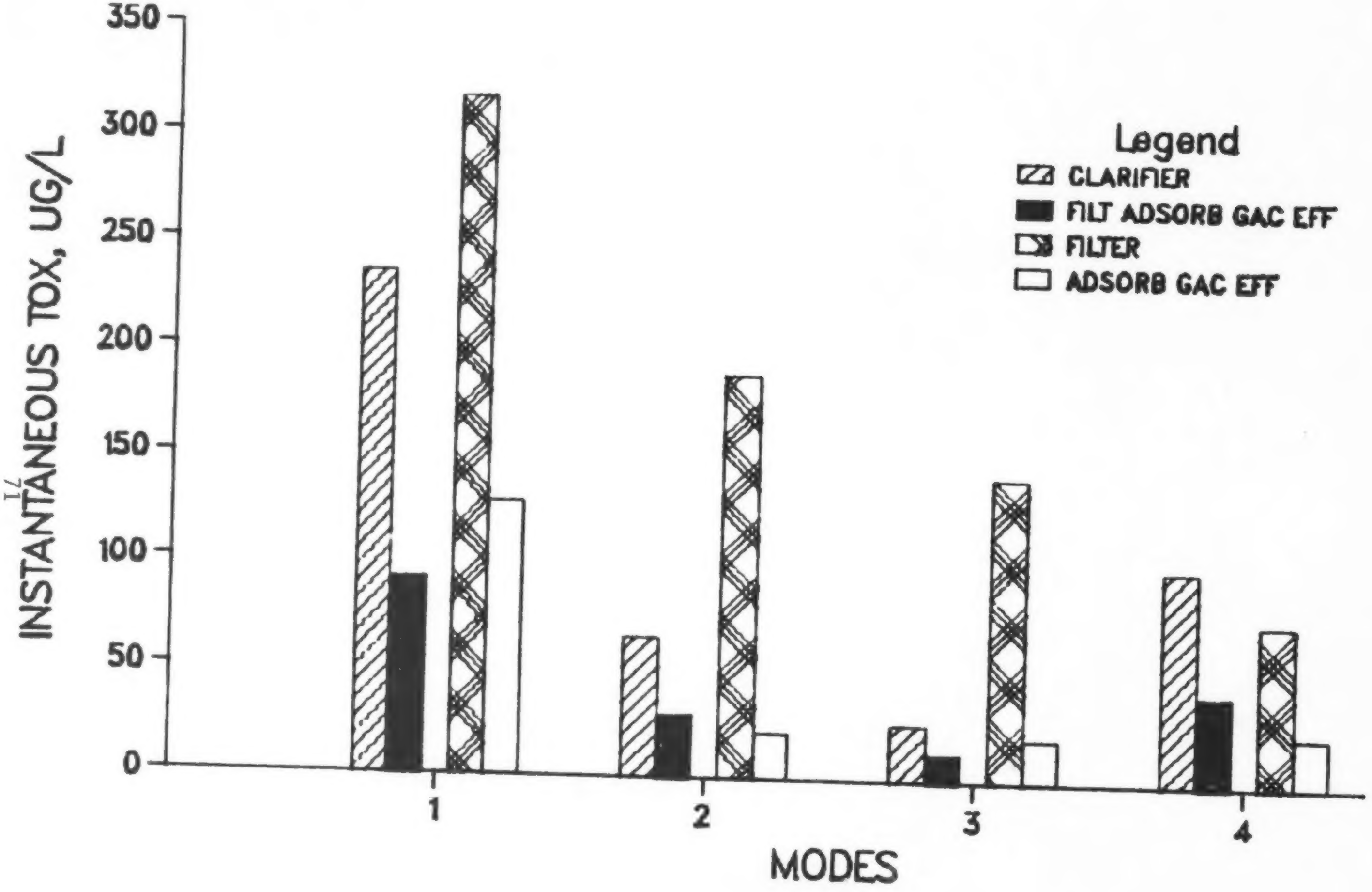


FIGURE 31. AVERAGE GAC PERFORMANCE DURING TREATMENT MODES—THORNTON, CO.

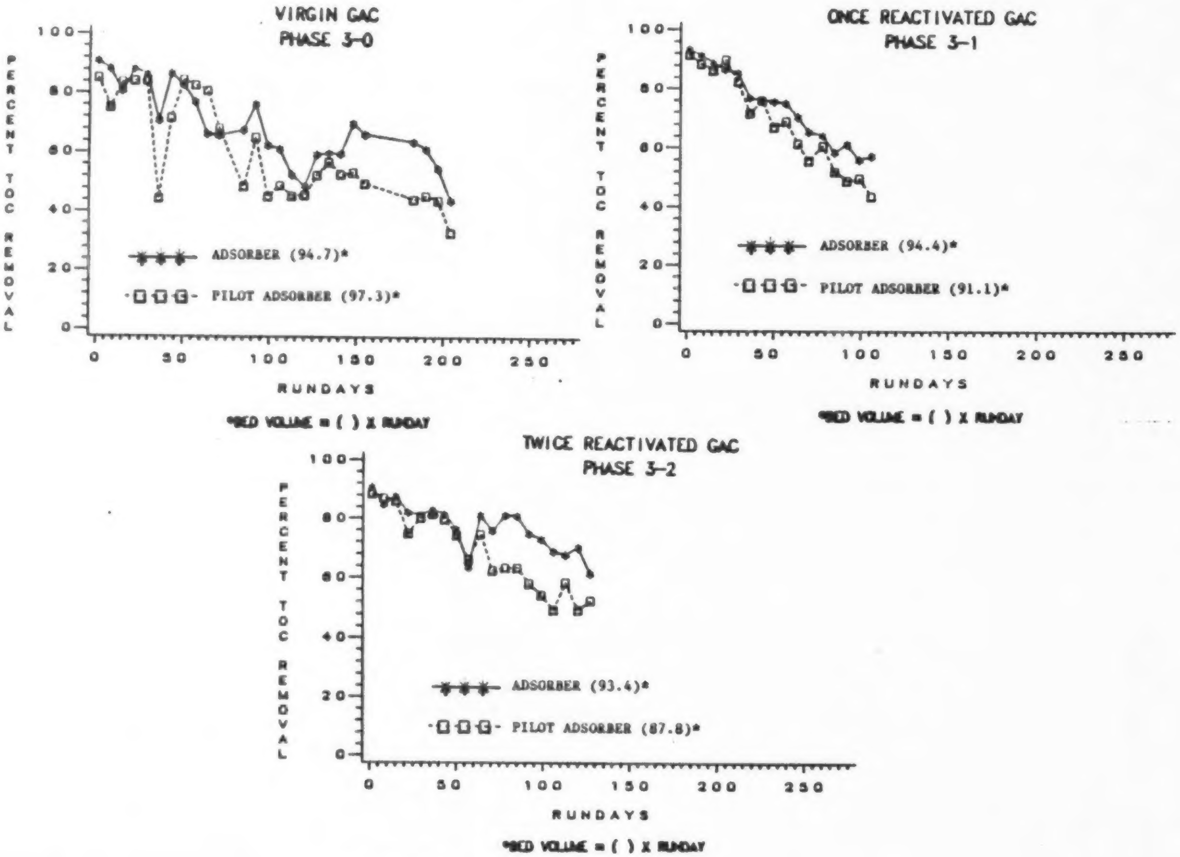


FIGURE 32. PREDICTION OF ADSORBER PERFORMANCE FOR TOC USING PILOT SIMULATION AT CINCINNATI, OHIO

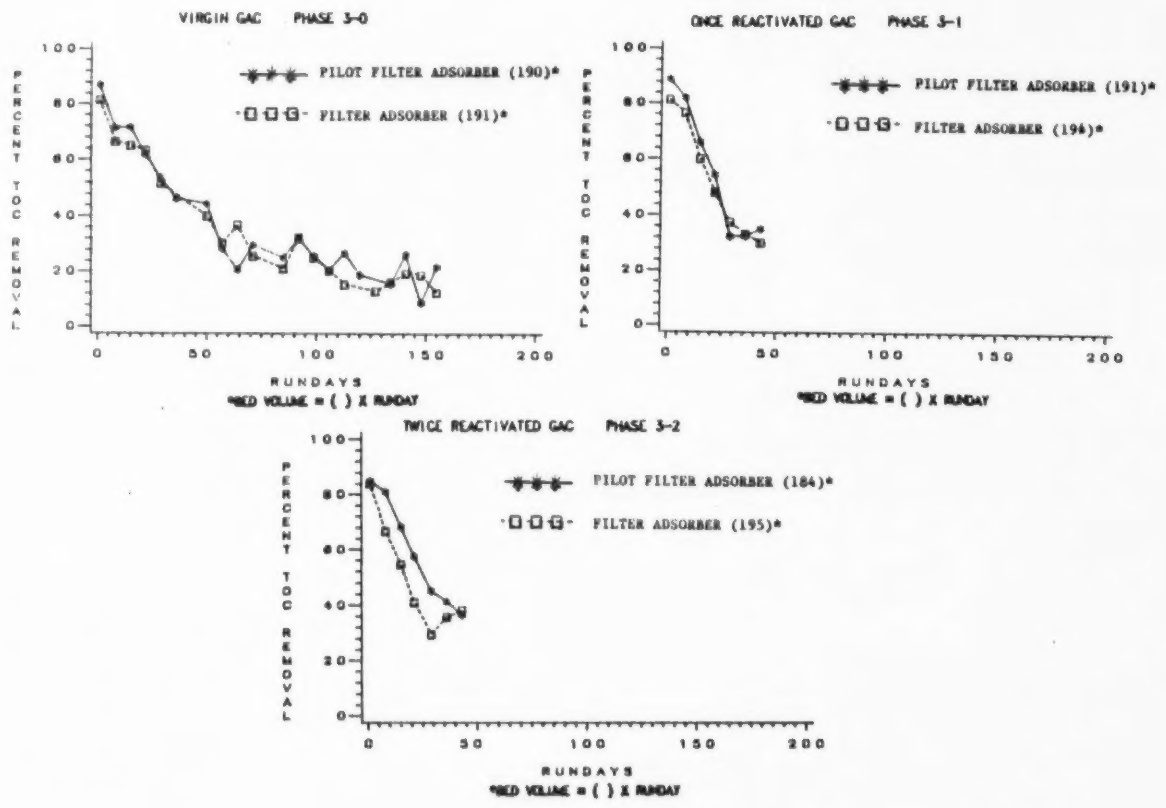


FIGURE 33. PREDICTION OF FILTER ADSORBER PERFORMANCE FOR TOC USING PILOT SIMULATION AT CINCINNATI, OHIO

At Jefferson Parish, Louisiana similar predictive performance was also noted with the pilot column simulators of the full-scale systems. As with the Cincinnati study, measurement and control of flow and GAC in both systems to maintain an equal situation was difficult. As shown in Table 18, the EBCT times were somewhat different between the pilot and full-scale systems although the hydraulic loadings were similar.

TABLE 18. AVERAGE EBCT OF PILOT AND FULL-SCALE SYSTEMS - JEFFERSON PARISH, LA

	Phase IIB Hydraulic Loading			Phase III Hydraulic Loading		
	(m/hr)	(gpm/ft^2)	EBCT	(m/hr)	(gpm/ft^2)	EBCT
Full-Scale Adsorber	2.6	1.07	17.0	2.3	0.95	18.8
Pilot Adsorber	2.4	1.00	21.2	2.2	0.90	21.7
Full-Scale Filter Adsorber	2.8	1.16	13.7	1.8	0.75	23.2
Pilot Filter Adsorber	2.7	1.13	16.8	2.2	0.90	20.7

This difference is also reflective in the comparative performance difference between the full-scale systems and their respective pilot simulators. For Phase IIB, the pilot adsorber removed on the average 8 percent more TOC than the full-scale adsorber and in Phase III 7 percent more (Figures 34 & 35). The pilot filter adsorber performance for TOC during Phase IIB showed an average 13 percent higher removal than did the sand replacement bed (Figure 36). Better pilot simulator performance was expected because of a longer EBCT but in Phase III the pilot simulator removed on the average 6 percent more TOC than the corresponding full-scale filter adsorber although the EBCT was 2.5 minutes less (Figure 37). As mentioned previously, flow rate measurements at times were difficult and can be a possible explanation for this discrepancy.

Examination of 1,2-dichloroethane, the most consistent specific organic identified at Jefferson Parish other than the trihalomethane species, showed similar pilot column predictive capabilities. For instance, in Phase IIB the pilot column simulator for both the adsorber and filter adsorber showed similar effluent concentrations as their full-scale counterparts (Figures 38 & 39). In Phase III, both the adsorber and the filter adsorber pilot column simulators exhibitied somewhat greater adsorption efficiencies than the full-scale systems (Figures 40 & 41).

Effects of EBCT

The length of GAC operation before replacement or reactivation depends on several factors, one of which is EBCT. If a utility is required to use existing filters, very little flexibility is available for selection of EBCT. In designing a new system, however, the utility has an opportunity to determine the best EBCT relative to performance criteria and cost.

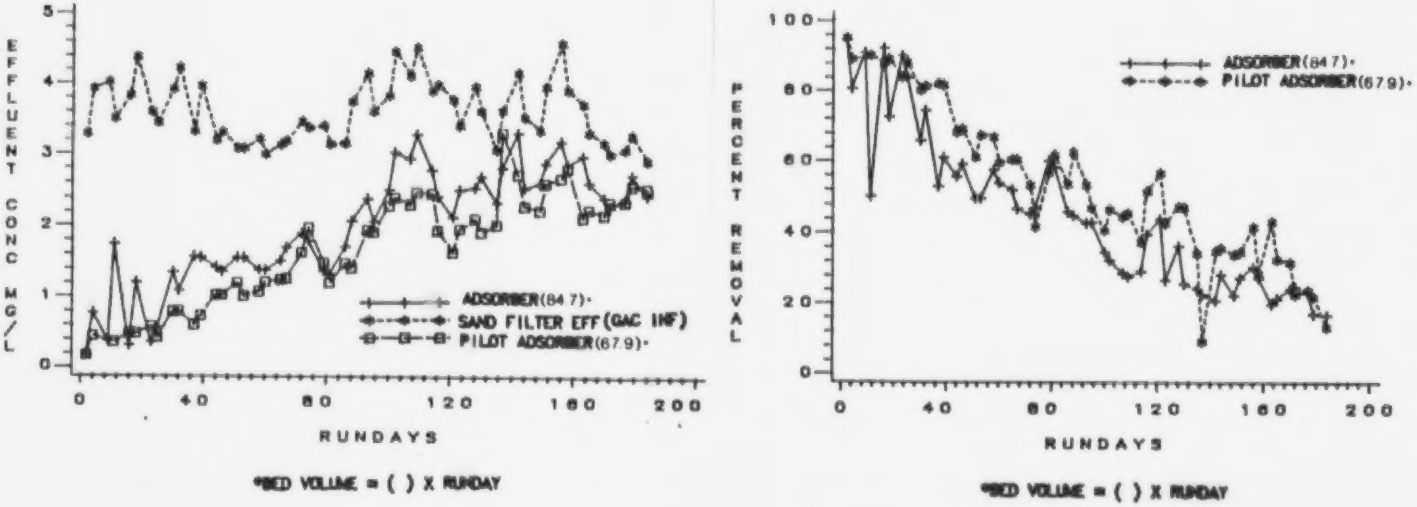


FIGURE 34. TOC EFFLUENT CONCENTRATION AND PERCENT REMOVAL VS. DAY OF RUN FOR THE ADSORBER AND THE ADSORBER SIMULATOR DURING PHASE 11B – JEFFERSON PARISH, LA.

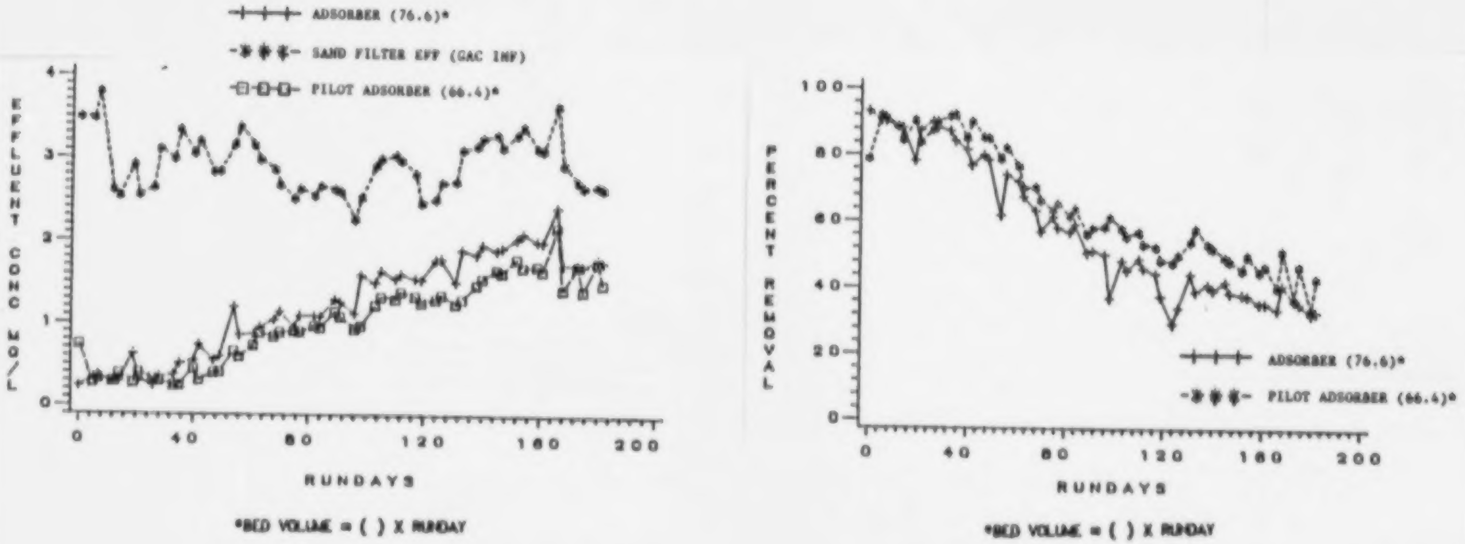


FIGURE 35. TOC REMOVAL FOR THE ADSORBER AND THE PILOT ADSORBER DURING PHASE I I I
— JEFFERSON PARISH, LA.

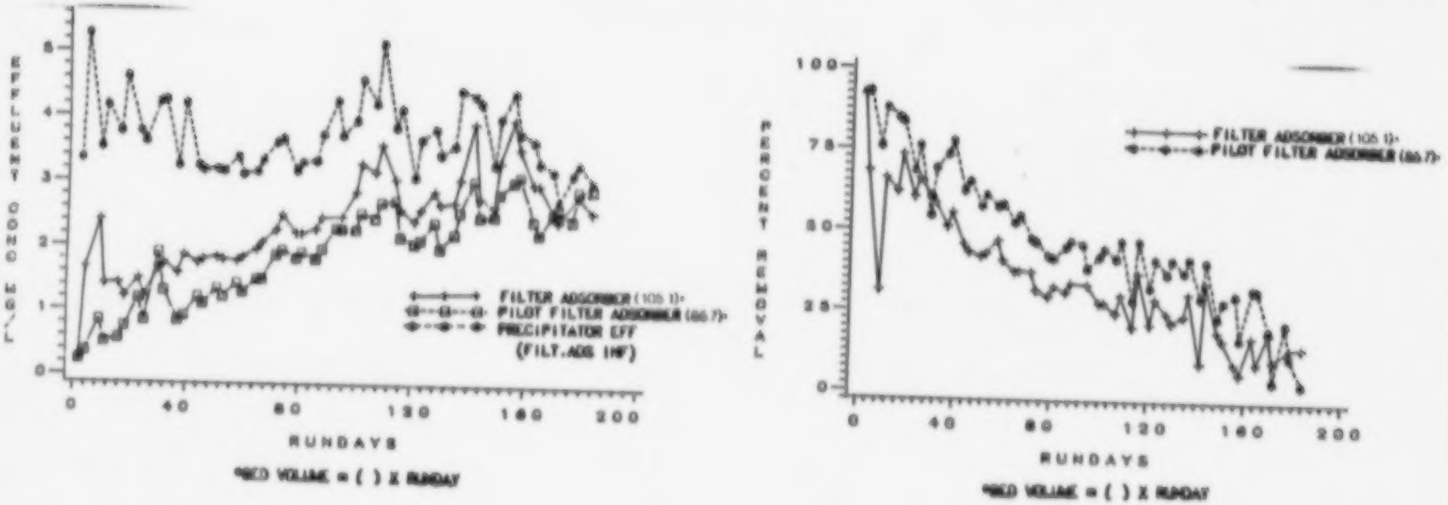


FIGURE 36. TOC REMOVAL FOR THE FILTER ADSORBER AND THE FILTER ADSORBER SIMULATOR DURING PHASE IIB – JEFFERSON PARISH, LA.

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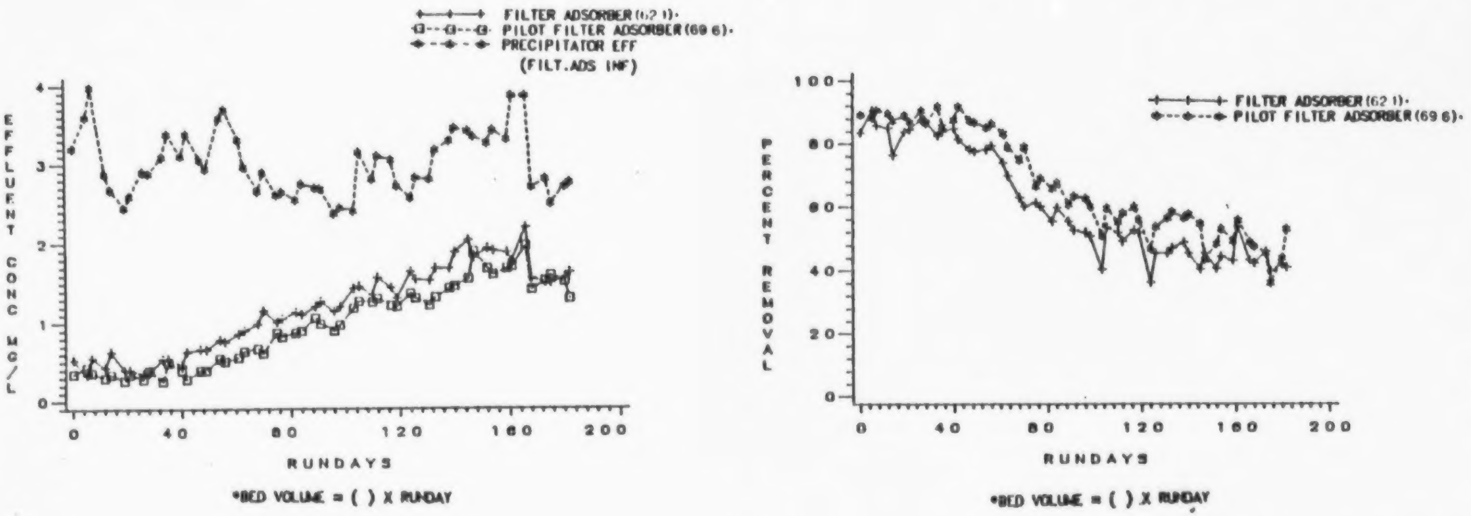

FIGURE 37. TOC REMOVAL FOR THE FILTER ADSORBER AND THE PILOT FILTER ADSORBER DURING PHASE III – JEFFERSON PARISH, LA.

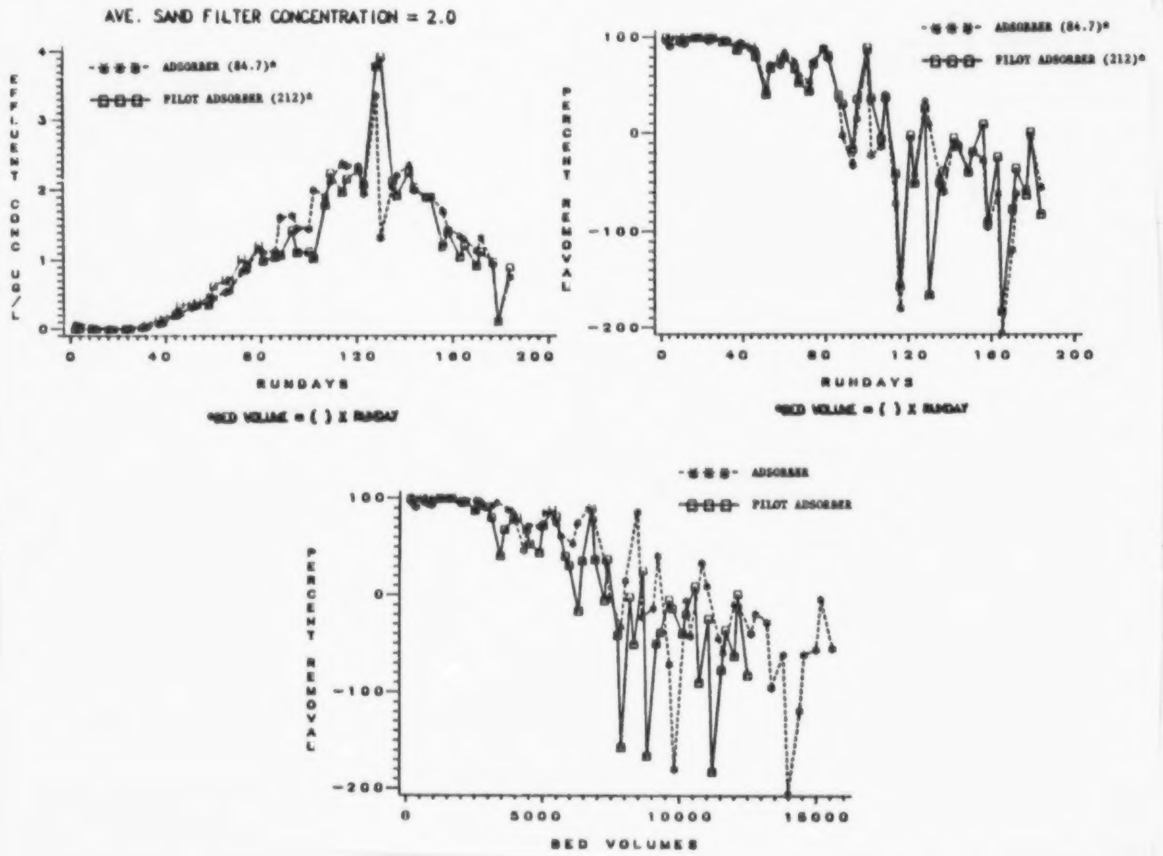

FIGURE 38. REMOVAL OF 1,2 DICHLOROETHANE THROUGH THE ADSORBER AND PILOT ADSORBER DURING PHASE IIB – JEFFERSON PARISH, LA.

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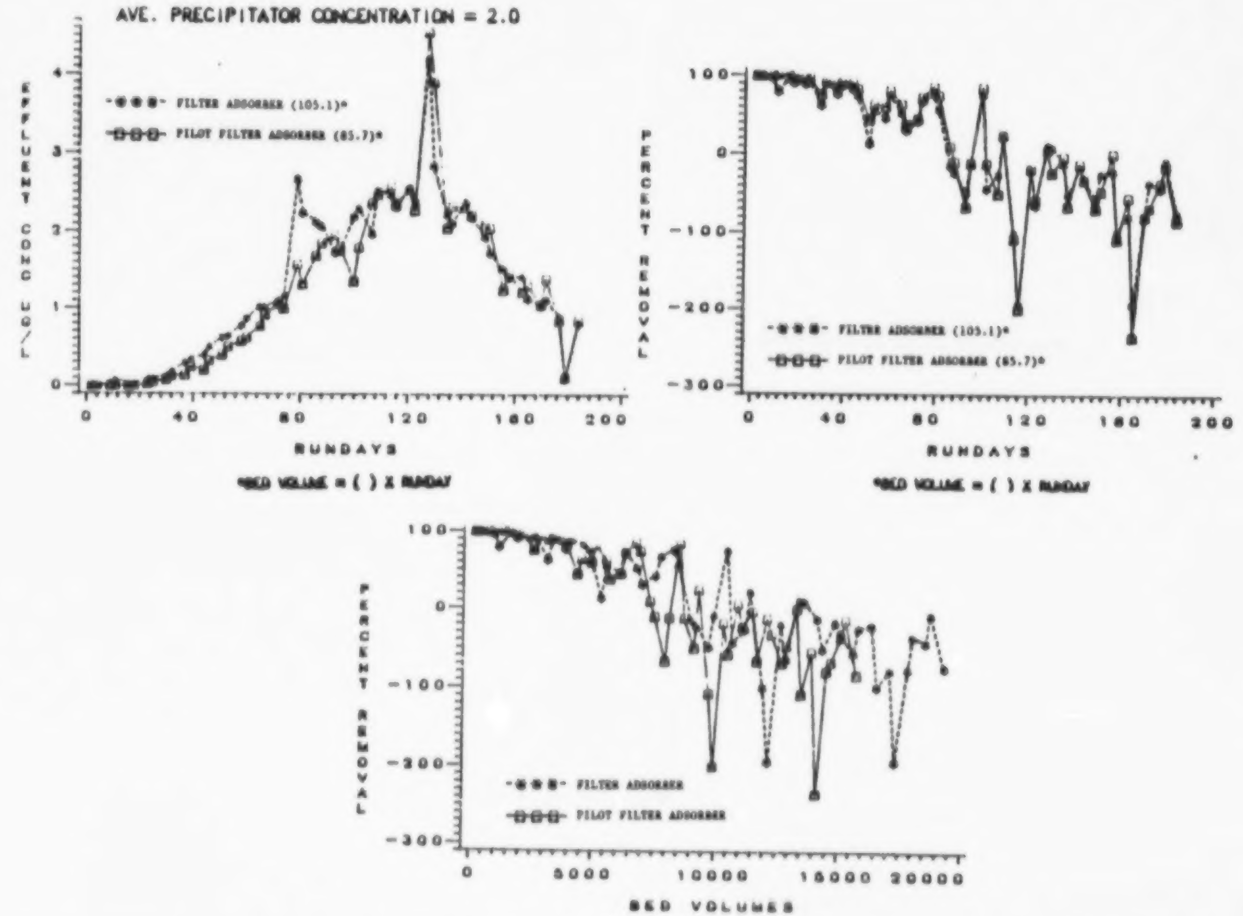


FIGURE 39. REMOVAL OF 1,2 DICHLOROETHANE THROUGH THE FILTER ADSORBER AND PILOT FILTER ADSORBER DURING PHASE IIB – JEFFERSON PARISH, LA.

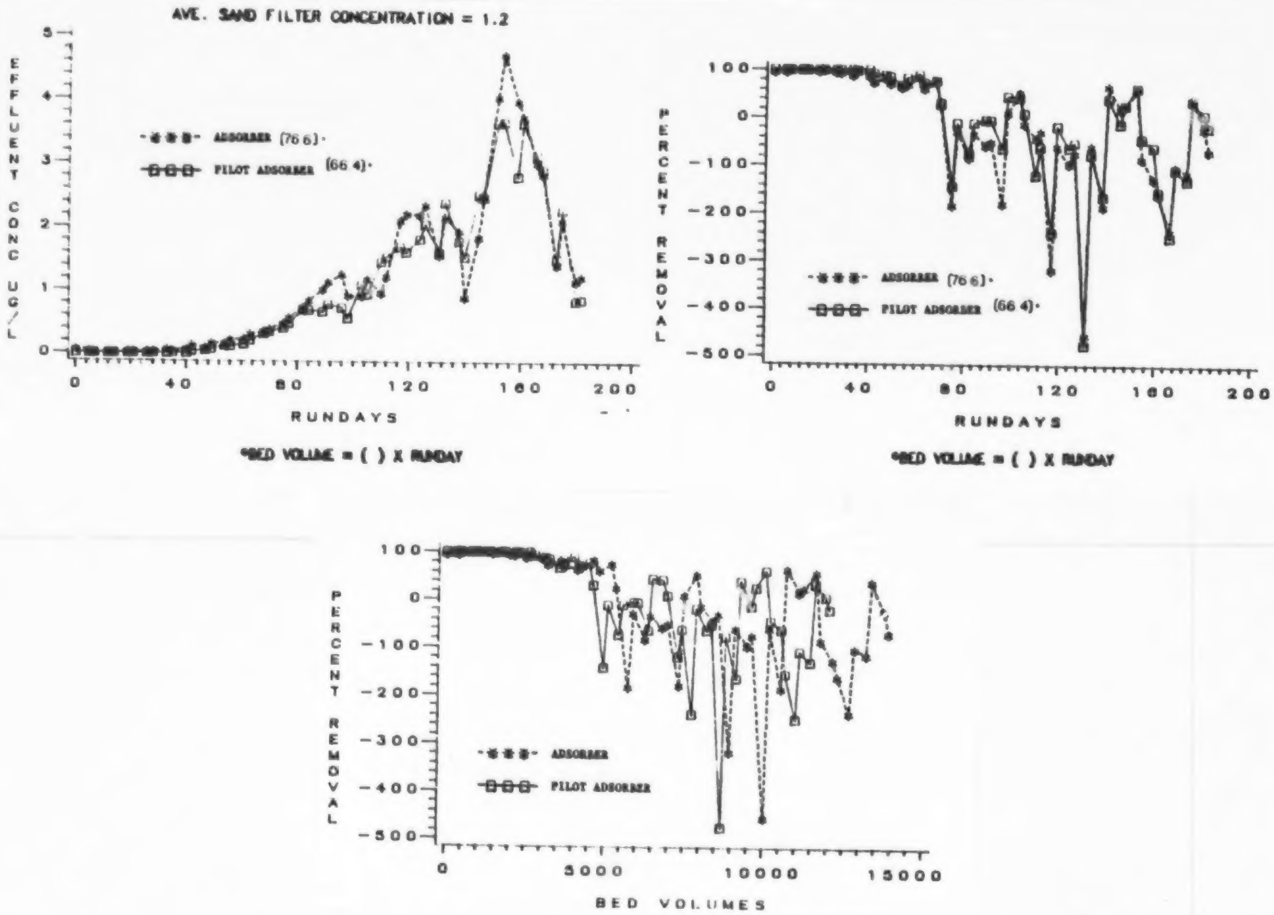


FIGURE 40. 1,2 DICHLOROETHANE EFFLUENT CONCENTRATION VS. DAY OF RUN FOR THE ADSORBER AND ADSORBER SIMULATOR DURING PHASE III – JEFFERSON PARISH, LA.

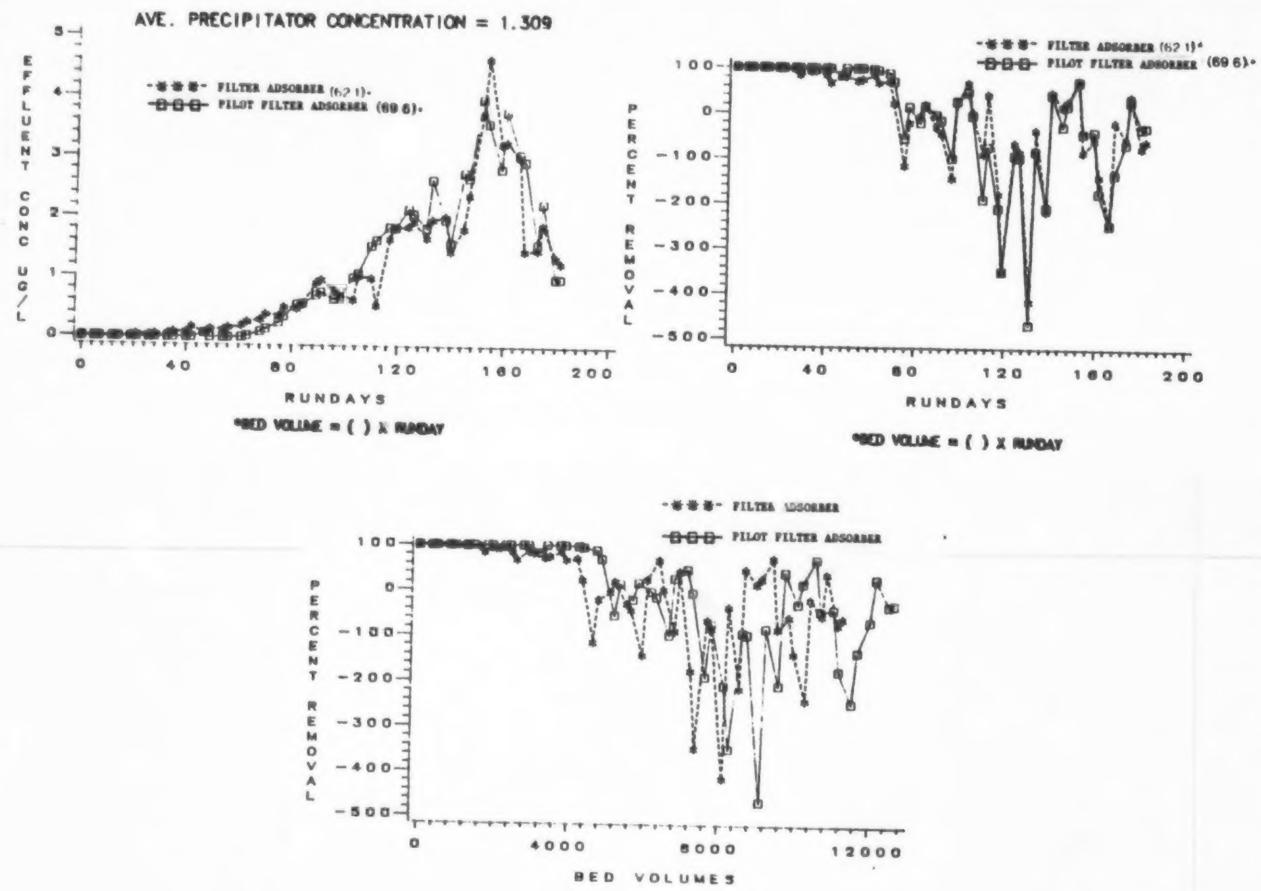


FIGURE 41. REMOVAL OF 1,2-DICHLOROETHANE THROUGH THE FILTER ADSORBER AND PILOT FILTER ADSORBER DURING PHASE III — JEFFERSON PARISH, LA.

A GAC exhaustion criteria of 1.0 mg/L TOC was selected by Cincinnati as a reasonable performance standard. Exhaustion was determined after the 1.0 mg/L criteria had been exceeded for three consecutive sampling days. This criteria will be used below to discuss the performance effects of varying EBCTs in lieu of a better criteria.

As shown previously, the GAC contactor depth at Cincinnati was 4.6 m (15 ft) with sampling ports located at various points along the contactors. Samples taken at 1.3 m (4.3 ft), 2.1 m (7.0 ft), and 4.6 m (15.0 ft) yielded EBCTs of 4.4, 7.2, and 15.2 minutes, respectively. By applying the aforementioned criteria to the TOC breakthrough curves for virgin GAC in Figure 42, one can see the effects of EBCT. Relating length of GAC operation to carbon use rate as summarized in Table 19 and shown in Figure 43 indicates that longer EBCTs provided more efficient use of the GAC.

TABLE 19. SUMMARY DATA AT TOC EXHAUSTION OF 1.0 mg/L
USING VIRGIN WVG® 12x40 GAC - CINCINNATI, OHIO

GAC Depth	EBCT (minutes)	Hydraulic Loading m/hr	Hydraulic Loading (gpm/ft^2)	TOC Exhaustion Time (Days)	Carbon Use Rate (Kg/mil L)	Organic Loading g/kg
1.3 m (4.3 ft.)	4.4	17.8	7.4	22	46	15
2.1 m (7.0 ft.)	7.2	17.8	7.4	71	34	25
4.6 m (15.0 ft.)	15.2	17.8	7.4	204	26	51

At Jefferson Parish, pilot columns were used to evaluate the effects of EBCT. By applying the same TOC exhaustion criteria (1.0 mg/L) to the four pilot series contactors as shown in Figure 44, one can see a longer operational time with increased EBCT through 31.4 minutes. Above that EBCT no apparent advantage is gained by additional contact time although some improvement in GAC effluent quality was noted. Essentially, a proportional increase in operation before exhaustion relative to EBCT was noted through 31.4 minutes (Table 20).

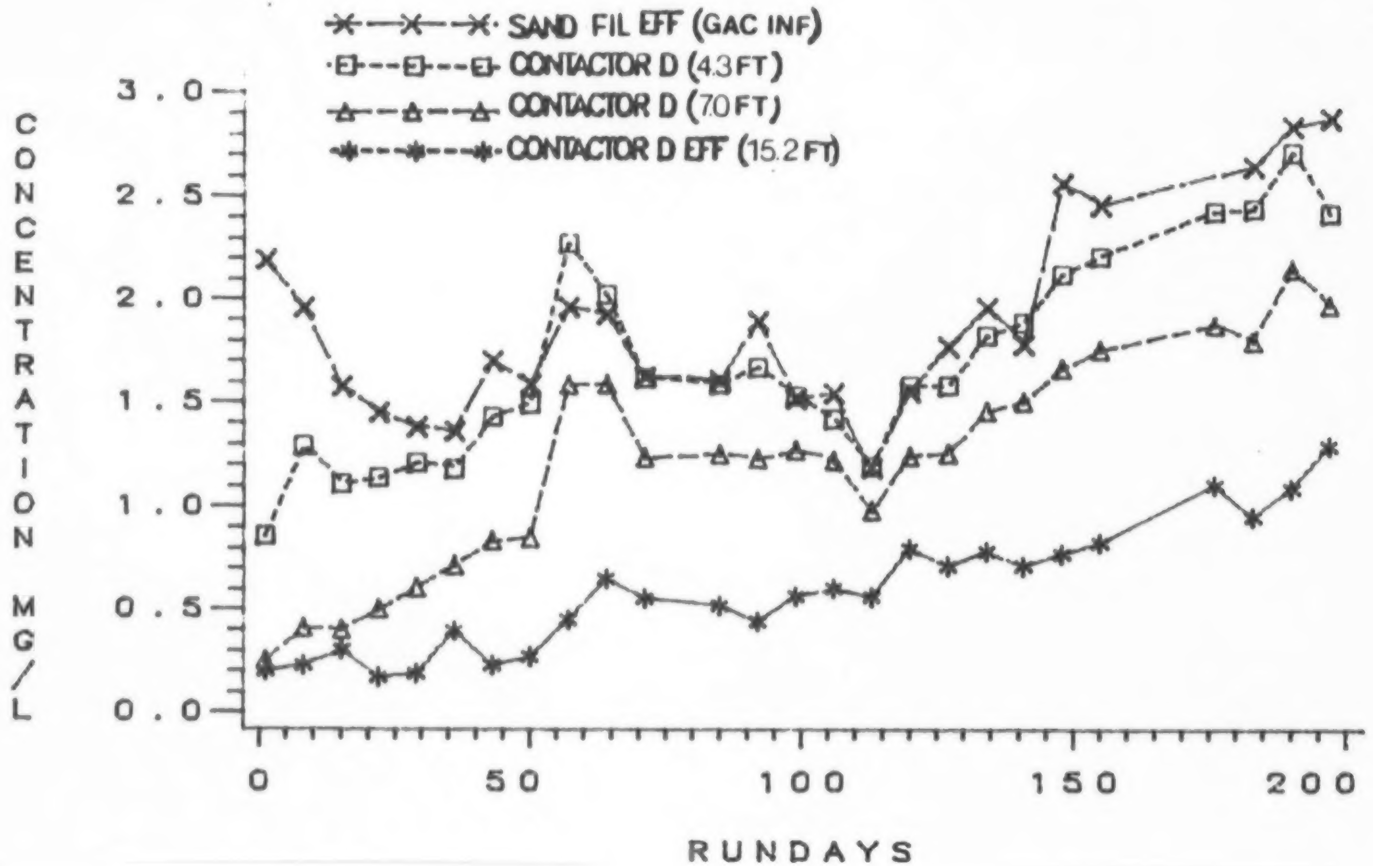
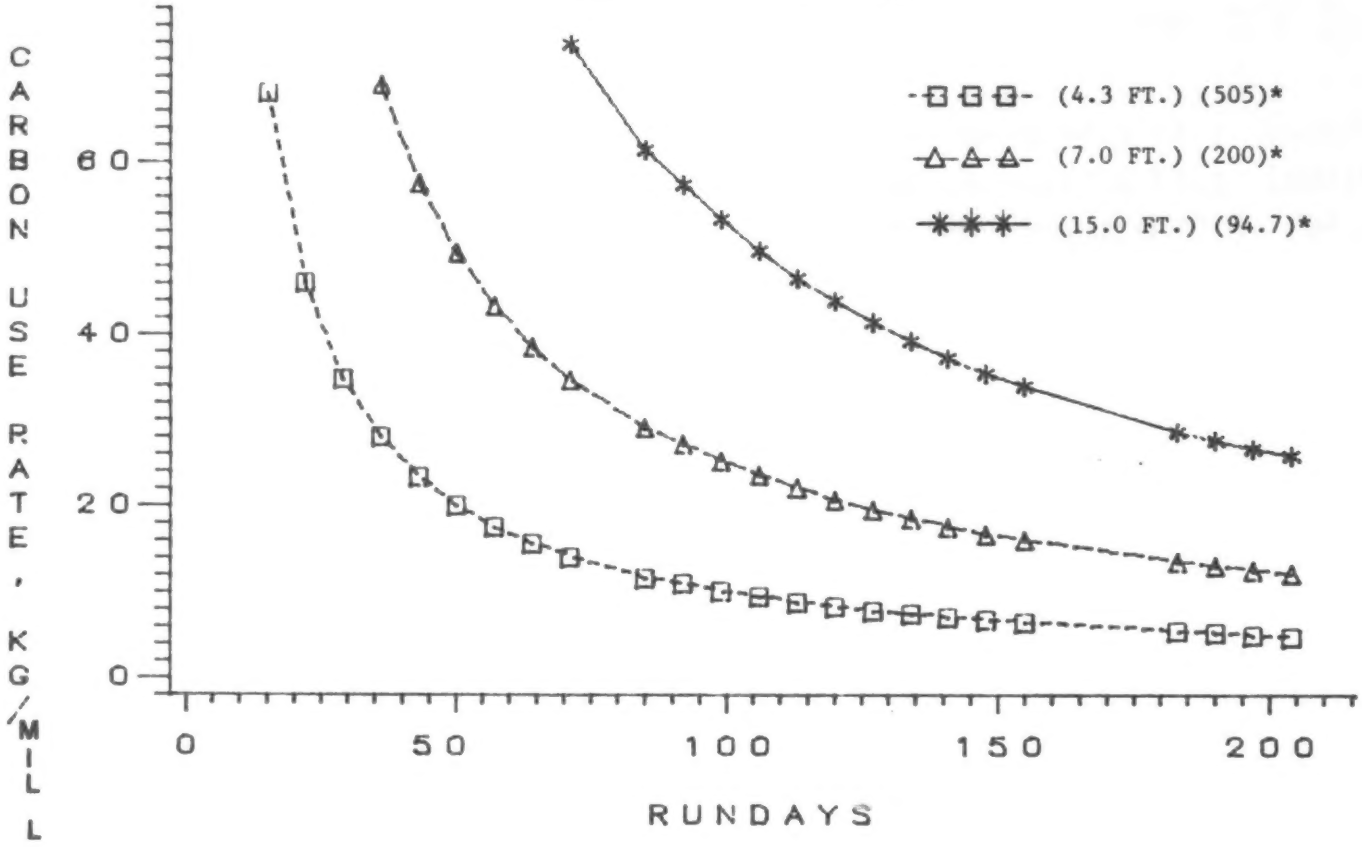
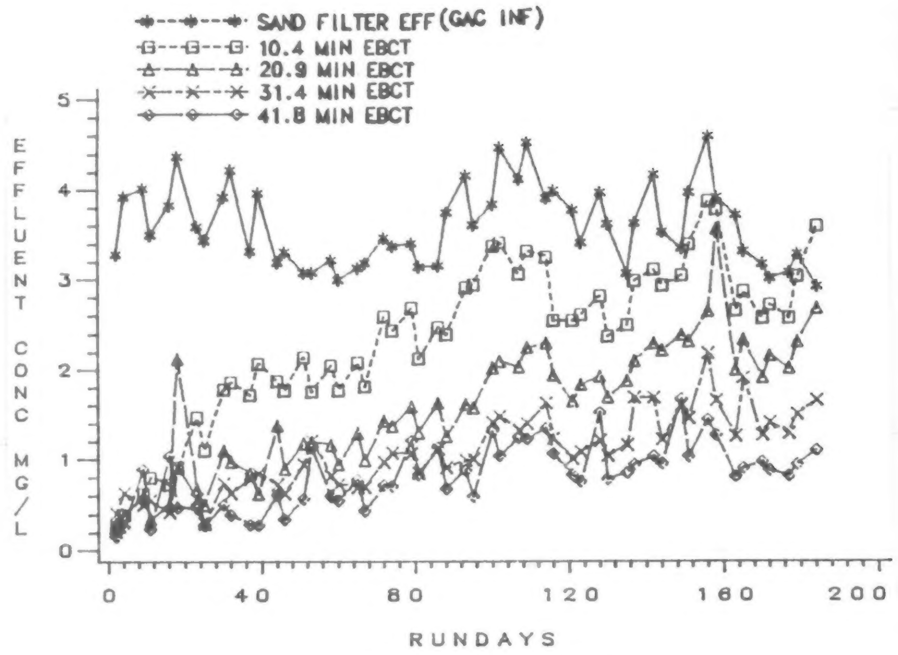


FIGURE 42. TOTAL ORGANIC CARBON BREAKTHROUGH CURVES FOR PHASE 3–0 (VIRGIN GAC) – CINCINNATI, OHIO



*BED VOLUME = ( ) X RUNDAY

FIGURE 43. CARBON USE RATE FOR TOC AT VARIOUS CONTACTOR BED DEPTHS DURING VIRGIN GAC EVALUATION AT CINCINNATI, OHIO



*BED VOLUME = ( ) X RUNDAY

FIGURE 44. COMPARISON OF TOC REMOVAL FOR VARIOUS CONTACT TIMES USING ADSORBERS WITH WVG$^{(R)}$ 12X40 GAC – JEFFERSON PARISH, LA.

TABLE 20. SUMMARY DATA AT TOC EXHAUSTION OF 1.0 mg/L USING VIRGIN WVG® 12x40 GAC - JEFFERSON PARISH, LA

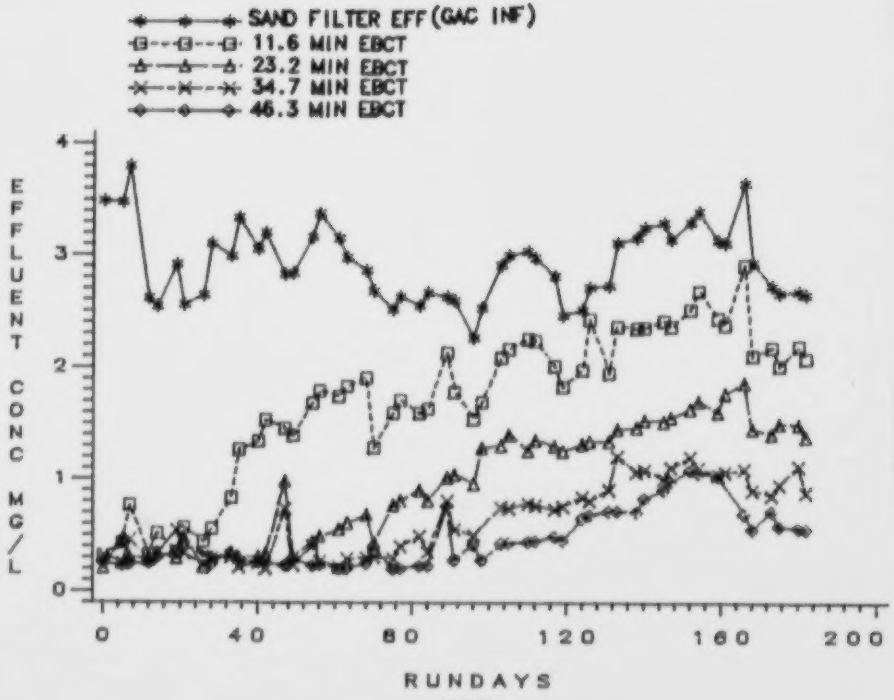
GAC Depth	EBCT (minutes)	Hydraulic $m^3/hr/m^2$	Loading (gpm/ft^2)	TOC Exhaustion Time (Days)	Carbon Use Rate (Kg/mil L)	Organic Loading g/kg
(36 in)	10.4	5.3	(2.16)	30	94	31
(72 in)	20.9	5.3	(2.16)	79	36	70
(108 in)	31.4	5.3	(2.16)	106	27	103
(144 in)	41.8	5.3	(2.16)	106	27	109

The above TOC data for Jefferson Parish was produced using the same type of GAC that was used at Cincinnati (WVG® 12x40). A different GAC (Filtrasorb® 400) was also evaluated at a different time period with a lower average applied TOC (3.6 vs 2.9 mg/L). Consequently, the days of operation for the Filtrasorb® 400 before exhaustion were longer (Figure 45) although the EBCTs were comparable (Table 20 & 21).

TABLE 21. SUMMARY DATA AT TOC EXHAUSTION OF 1.0 mg/L USING VIRGIN F400® GAC - JEFFERSON PARISH, LOUISIANA

GAC Depth	EBCT (minutes)	Hydraulic $m^3/hr/m^2$	Loading (gpm/ft^2)	TOC Exhaustion Time (Days)	Carbon Use Rate (Kg/mil L)	Organic Loading g/kg
(36 in)	11.6	4.9	(2.02)	42	73	32
(72 in)	23.2	4.9	(2.02)	105	30	78
(108 in)	34.7	4.9	(2.02)	140	22	107
(144 in)	46.3	4.9	(2.02)	159	20	126

In Miami, Florida series pilot columns were used to produce an ultimate EBCT of 24.8 minutes at a hydraulic loading of 7.2 m/hr (3 gpm/ft^2). The finished water TOC concentration at Miami is generally in the area of 5 mg/L as compared to Cincinnati and Jefferson Parish ranges of 2 to 4 mg/L. Using the same GAC exhaustion criteria (1.0 mg/L TOC), indications



*BED VOLUME = ( ) X RUNDAY

FIGURE 45. COMPARISON OF TOC REMOVAL FOR VARIOUS CONTACT TIMES USING ADSORBERS WITH F400$^{(R)}$ GAC – JEFFERSON PARISH, LA.

are that at Miami carbon operation before exhaustion is less than was seen at Cincinnati and Jefferson Parish at various EBCTs (Figure 46 and Table 22).

If the GAC criteria, however, were selected at Miami when a plateau occurs in the breakthrough curve (steady-state) then the operational time could be extended significantly. For instance, at 24.8 minutes EBCT the 1.0 mg/L TOC criteria would allow 35 days before exhaustion and the plateau method 60 days. The performance loss by allowing the GAC adsorber to continue operating until steady state at Miami would be an average increase in effluent concentration of 2.2 mg/L at 24.8 minutes EBCT (total TOC effluent concentration is 3.2 mg/L).

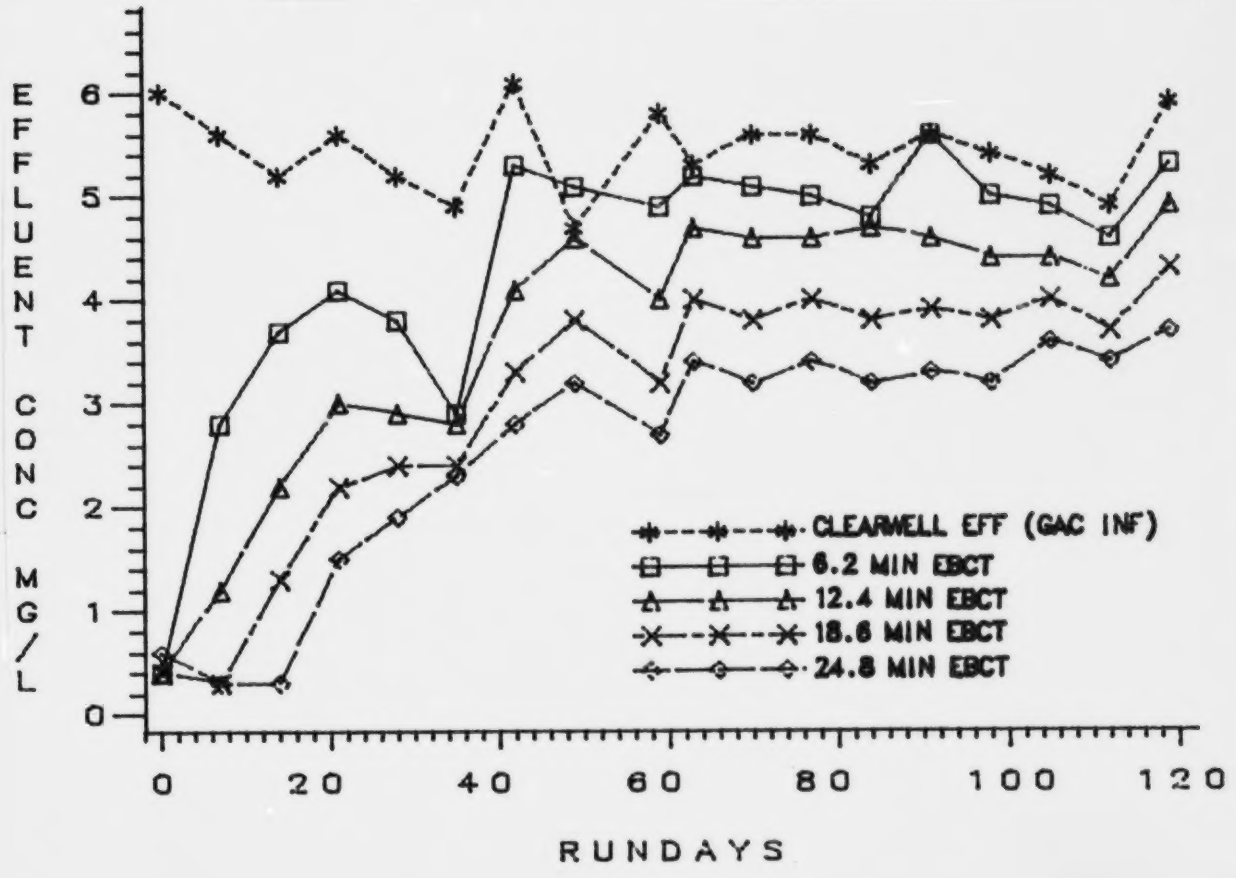
TABLE 22. SUMMARY DATA AT TOC EXHAUSTION OF 1.0 mg/L USING F400® GAC - MIAMI, FLORIDA

GAC Depth	EBCT (minutes)	Hydraulic Loading $m^3/hr/m^2$	(gpm/ft^2)	TOC Exhaustion Time (Days)	Carbon Use Rate (Kg/mil L)	Organic Loading g/kg
(2.5 ft)	6.2	7.3	(3.0)	21	92	23
(5.0 ft)	12.4	7.3	(3.0)	21	92	39
(7.5 ft)	18.6	7.3	(3.0)	28	69	60
(10. ft)	24.8	7.3	(3.0)	35	55	78

The effects of EBCT were also evaluated for specific organics when they were present. For instance, in Jefferson Parish, 1,2-dichloroethane was detected consistently enough to evaluate. When using WVG® 12x40 GAC, saturation as determined by zero percent removal was 80, 110, and 160 days for 10.4, 20.9, and 31.4 minutes EBCT, respectively. For 41.8 minutes EBCT, saturation had not occurred after 180 days of operation. Desorption occurred at varying degrees for each EBCT that experienced saturation (Figure 47).

A somewhat different time of saturation was noted for the F400® GAC as shown in Figure 47. After 11.6, 23.2, 34.7, and 46.3 minutes EBCT, saturation occurred in 70, 110, 130, and 160 days, respectively. This GAC seemed to perform similarly to the WVG® up to about 23 minutes EBCT but after that the WVG® removed the 1,2-dichloroethane more effectively even at a higher average GAC influent concentration (2.0 vs 1.2 ug/L). This performance difference is also illustrated by the mass loading (Figure 48).

In Miami, Florida the average GAC influent concentration of 1,2-dichloroethane was 19.9 ug/L; considerably higher than at Jefferson Parish. Although this was the case, the length of GAC operation before saturation



*BED VOLUME = ( ) X RUNDAY

FIGURE 46. COMPARISON OF TOC REMOVAL FOR VARIOUS CONTACT TIMES USING ADSORBERS WITH F400$^{(R)}$ GAC – MIAMI, FLORIDA

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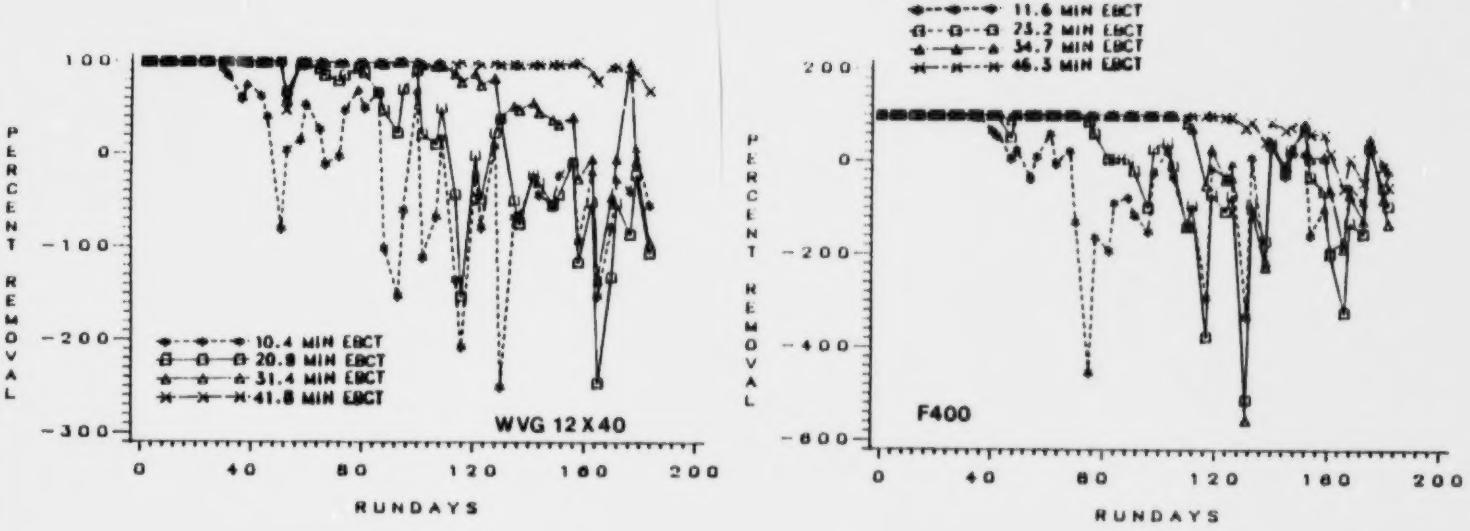

FIGURE 47. PERCENT REMOVAL OF 1,2-DICHLOROETHANE – JEFFERSON PARISH, LA.

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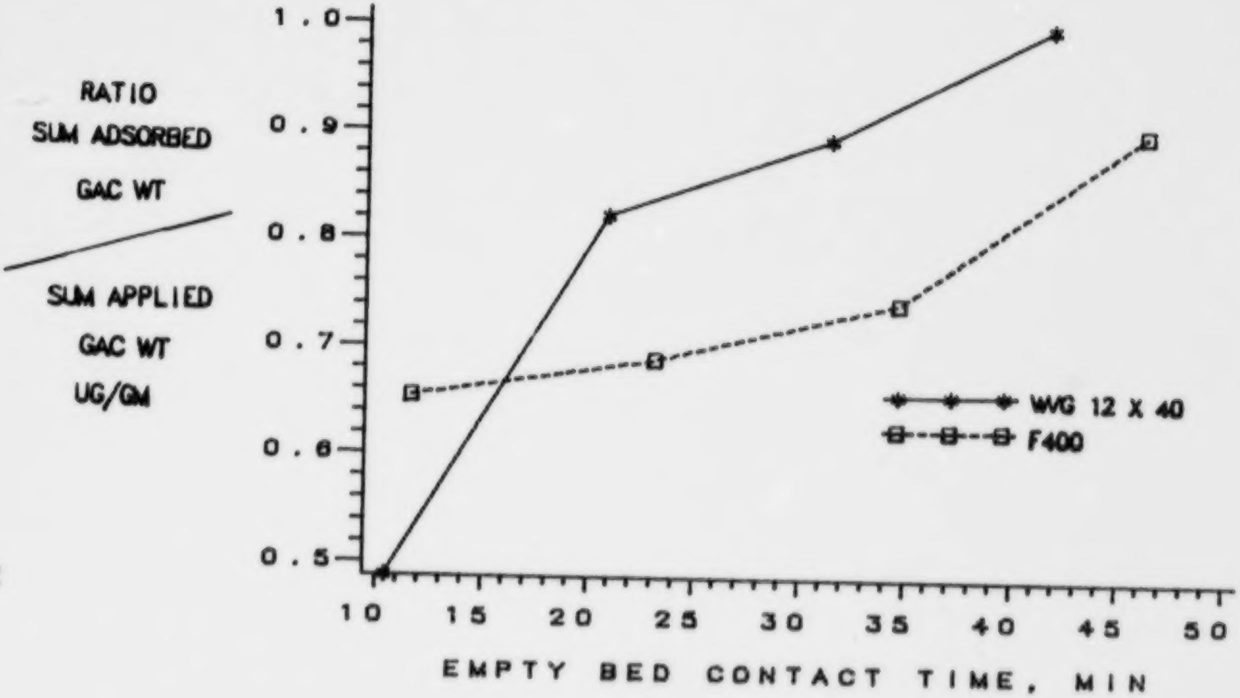

FIGURE 48. RATIO OF 1,2–DICHLOROETHANE ADSORBED/APPLIED VERSUS EBCT FOR TWO TYPES OF CARBONS – JEFFERSON PARISH, LA.

was much longer than at Jefferson Parish indicating that competitive adsorption was probably much greater at Jefferson Parish although the same type of GAC was used (F400®) as shown in Table 23.

TABLE 23. GAC SATURATION USING PLATEAU (STEADY-STATE) CRITERIA FOR 1,2-DICHLOROETHANE

Location	Avg. GAC Inf. Concentration (ug/L)	EBCT	Days to Saturation
Jefferson Parish, LA	1.2	11.6	70
		23.2	110
		34.7	130
		46.3	160
Miami, FL	19.9	6.2	66
		12.4	119
		18.6	171
		24.8	>180

Comparison of Different GAC Types

GACs produced from different base products are available for use in drinking water applications.(11) Although these GACs may have the same mesh size their performance for a particular water may be different. Therefore, before a GAC is selected for use in full-scale treatment, its performance should be considered along with the cost.

During three field-scale research projects, various GACs were evaluated. At each location the GACs were evaluated in parallel receiving the same influent water. At Passaic these evaluations were done during the duration of the project. Before starting research at Miami and Jefferson Parish, an initial screening of GAC performance was used for carbon selection. In the GAC screening at Miami, four commercially available carbons were selected for study (Table 24)(12).

TABLE 24. GRANULAR ACTIVATED CARBONS EVALUATED DURING SELECTION STUDY - MIAMI, FLORIDA

Manufacturer	Trade Name	Mesh Size
Calgon	Filtrasorb 400®	12 x 40
Westvaco	Nuchar WVG®	12 x 40
ICI	Hydrodarco 1030®	10 x 30
Witco	Witcarb 950®	12 x 30

For the evaluation at Miami, glass columns 2.5 cm (1 in) in diameter and 1.5 m (5 ft) in height with an EBCT of 6.2 min. were used. Each column contained 0.8 m (2.5 ft) of carbon and received clearwell finished water from the Preston Treatment Plant for the 59 day test period.

The selection criteria used at Miami was the total TOC and trihalomethane formation potential (THMFP) removed during the test period. Bed life exhaustion was determined as column breakthrough of TOC and THMFP of 3 mg/L and 200 ug/L, respectively. When using this criteria, Filtrasorb 400® had the longest bed life for TOC at 10 days. If one looks at TOC steady-state conditions, however, both Filtrasorb 400® and Nuchar WVG® appear to perform equally (Figure 49).

For THMFP at 200 ug/L breakthrough, Filtrasorb 400® again had the longest bed life of 10 days and the most THMFP adsorbed within the ten day period. Over the total test period, however, Filtrasorb 400 and Nuchar WVG again performed about the same as shown in Figure 50 and Table 25.

TABLE 25. TRIHALOMETHANE FORMATION POTENTIAL ADSORBED BY FOUR GACs - MIAMI, FLORIDA

Type of GAC	THMFP Applied to GAC, mg		THMFP Adsorbed, mg	
	10 Days	59 days	10 Days	59 Days
Filtrasorb 400®	172	2,002	92.6	524
Nuchar WVG®	172	2,002	60.3	545
Hydrodarco 1030®	172	2,002	23.7	314
Witcarb 950®	172	2,002	15.1	160

Chloroform adsorption was not a GAC selection criteria at Miami. The performances of the four GACs, however, were evaluated for removal of chloroform as an indicator of low molecular weight specific organic adsorption (Figure 51). The least performer for the high molecular weight organics as indicated by TOC and THMFP was the best adsorber for chloroform (Whitcarb 950®).

Glass columns 7.6 cm (3 in) in diameter and 1.8 m (6 ft) in height containing 0.8 m (30 in) of GAC at an EBCT of 15 minutes were used at Jefferson Parish for evaluating the performance of various carbons. Over a six-month period five different commercially available GACs were evaluated (Table 26)(13). Sand filter effluent from Jefferson Parish's treatment plant was applied to each column.

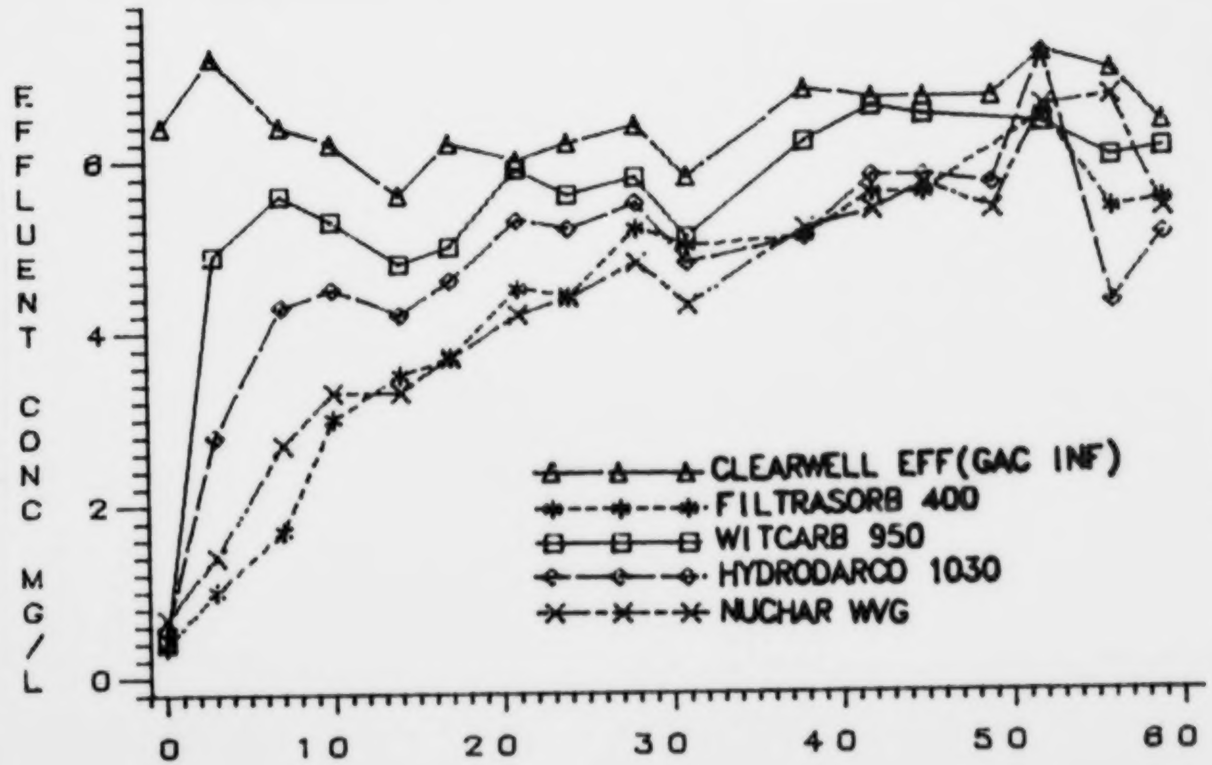

FIGURE 49. TOC BREAKTHROUGH CURVES FOR FOUR TYPES OF GACs – MIAMI, FLORIDA

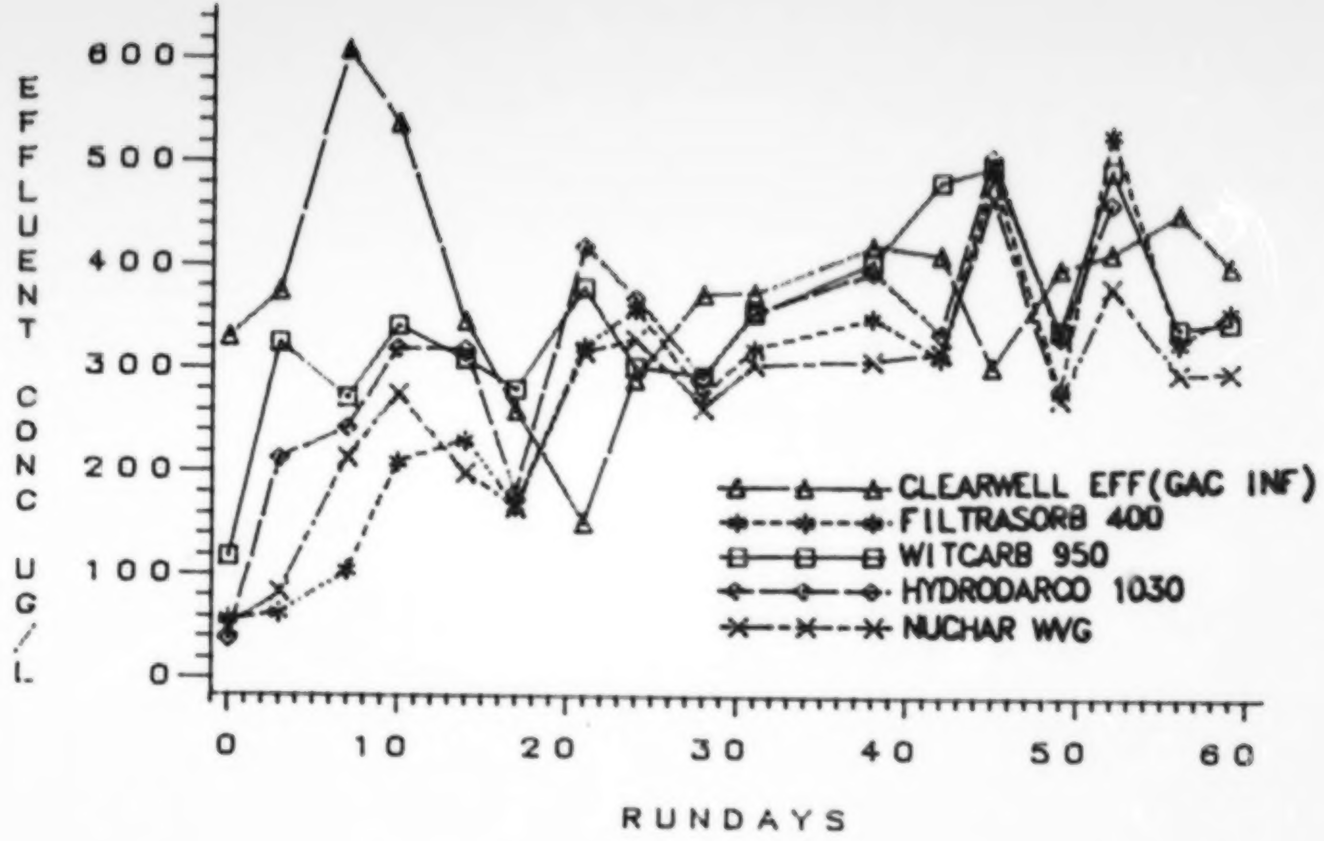

FIGURE 50. THMFP BREAKTHROUGH CURVES FOR FOUR TYPES OF GACs – MIAMI, FLORIDA

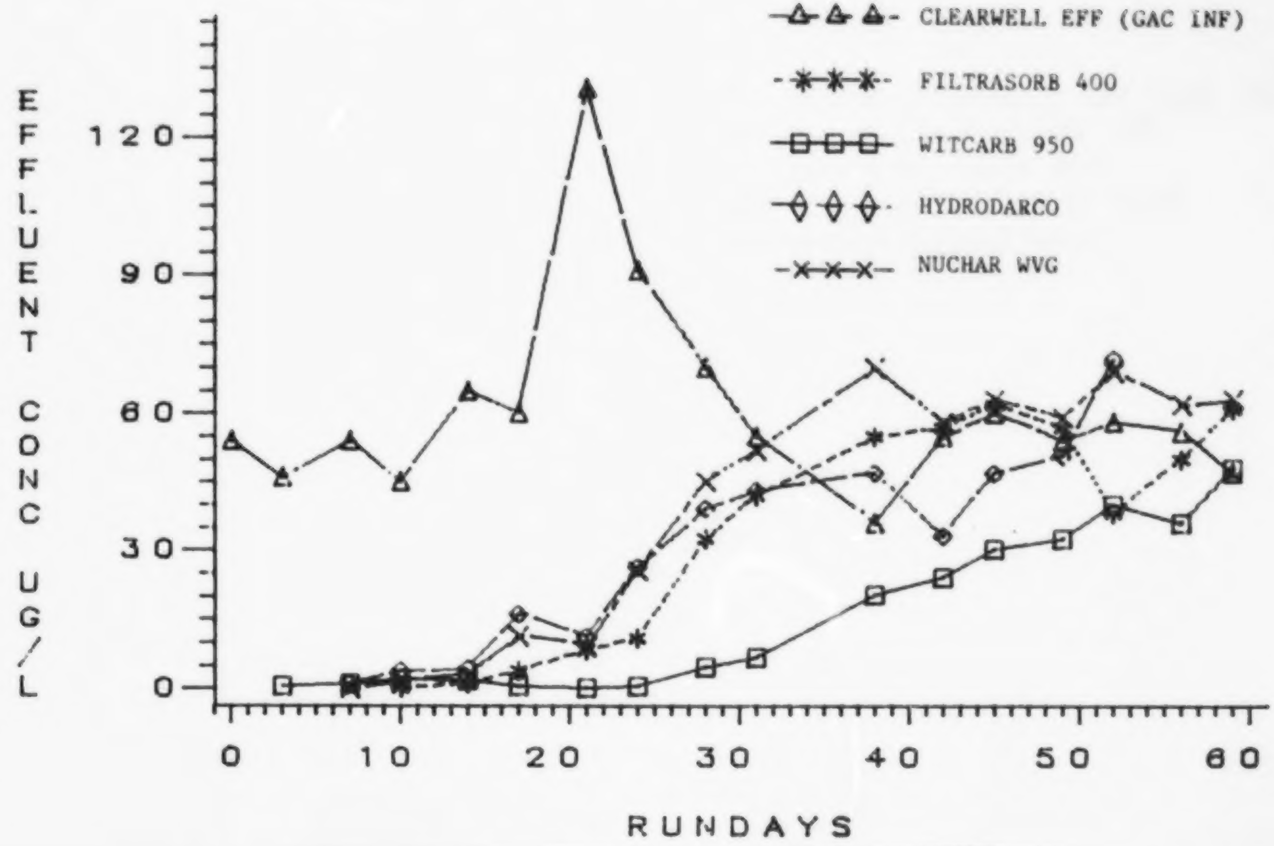

FIGURE 51. CHLOROFORM BREAKTHROUGH CURVES FOR FOUR TYPES OF GACs – MIAMI, FLORIDA

TABLE 26. GRANULAR ACTIVATED CARBONS EVALUATED DURING SELECTION STUDY AT JEFFERSON PARISH, LOUISIANA

Manufacturer	Trade Name	Mesh Size
Calgon	Filtrasorb 400®	12 x 40
Carborundum	GAC 40®	12 x 40
ICI	Hydrodarco 4000®	12 x 40
Norit	ROW 0.8 Supra®	0.8 mm diameter(a)
Westvaco	WV-G®	12 x 40

(a)pelletized cylinders varying in length from 1-2 mm.

Parameters monitored during this evaluation were: non-volatile TOC (NVTOC), instantaneous THMs, THMFP, 1,2-dichloroethane, electron capture total area (ECTOAR)† and flame ionization total area (FITOAR).† Effluent NVTOC for each GAC is presented in Figure 52. Visual observation of this figure for selection of the best performer is difficult although WV-G® seems to have performed slightly better than the others. This is reaffirmed by the average NVTOC effluent concentrations: WVG, 2.14 mg/L; GAC 40, 2.33 mg/L; Filtrasorb 400, 2.36 mg/L; ROW 0.8 supra, 2.42 mg/L; and Hydrodarco 4000, 2.87 mg/L.

While evaluating the various GACs at Jefferson Parish, a higher than normal influent concentration of 1,2-dichloroethane was noted during the early part of the evaluation (day 20-40). This high concentration (>10 ug/L) may have affected the length of run before the GAC became saturated. Saturation (1,2-dichloroethane) occurred for all of the GACs between day 50 and 80. Westvaco's WVG® reached saturation at day 80 and Calgon's F400® at day 50. The other GACs fell in between (Figure 53). There was relatively little difference in the adsorption efficiencies of the various carbons with respect to flame ionization and electron capture total area.

Prior to evaluation of the various GACs at Jefferson Parish, the initial organic load on each type of GAC was examined by Soxhlet extraction of 60 grams of carbon with hexane for 8 hours. The electron capture chromatograms showed essentially no contamination but a considerable amount of

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†Total area under chromatogram, excluding the solvent front, of the sample as compared to the external standards. Gas chromatographs were operated at 180°C isothermal for ECTOAR and 40-220°C at 4°C/min. with a 10 min. hold at 40°C for FITOAR.

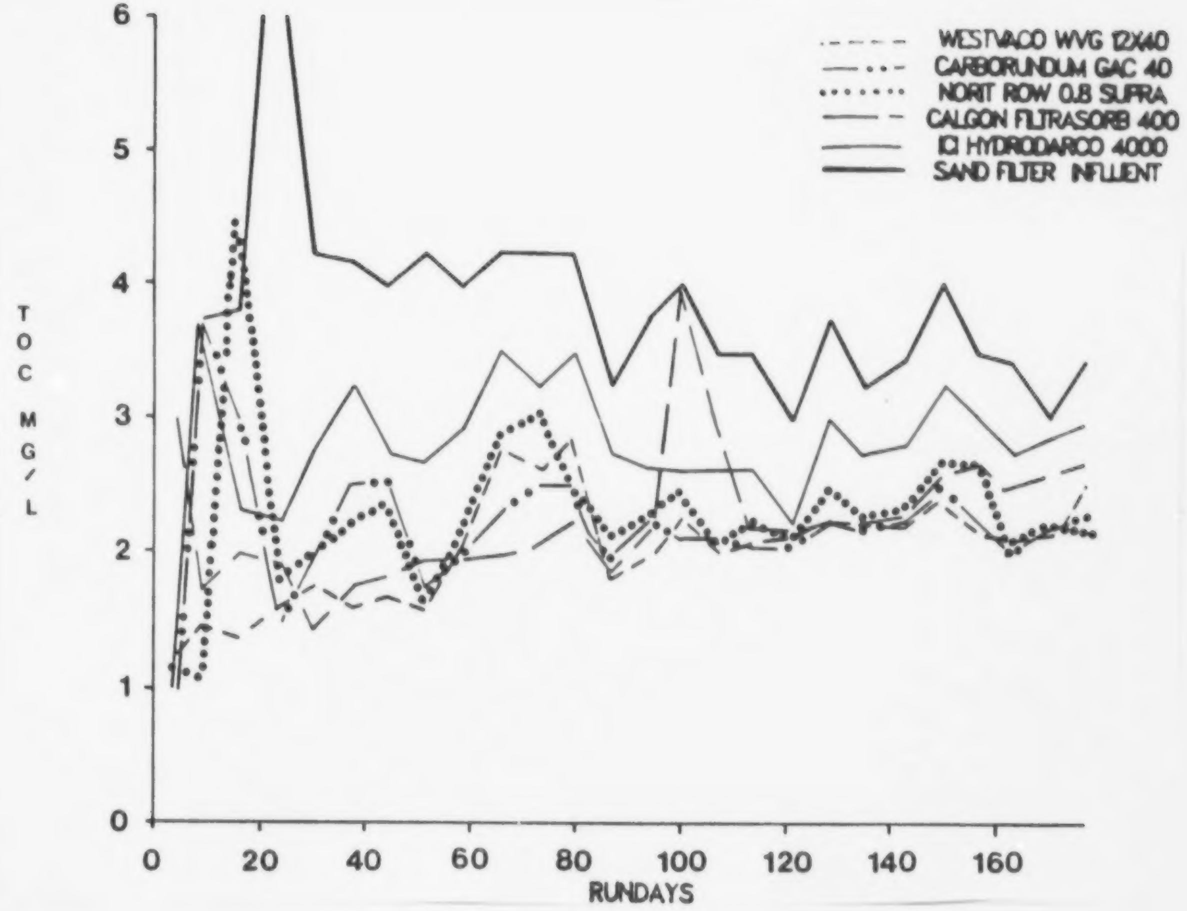

FIGURE 52. EFFLUENT TOC CONCENTRATIONS FOR EACH TYPE OF CARBON EVALUATED – JEFFERSON PARISH, LA.

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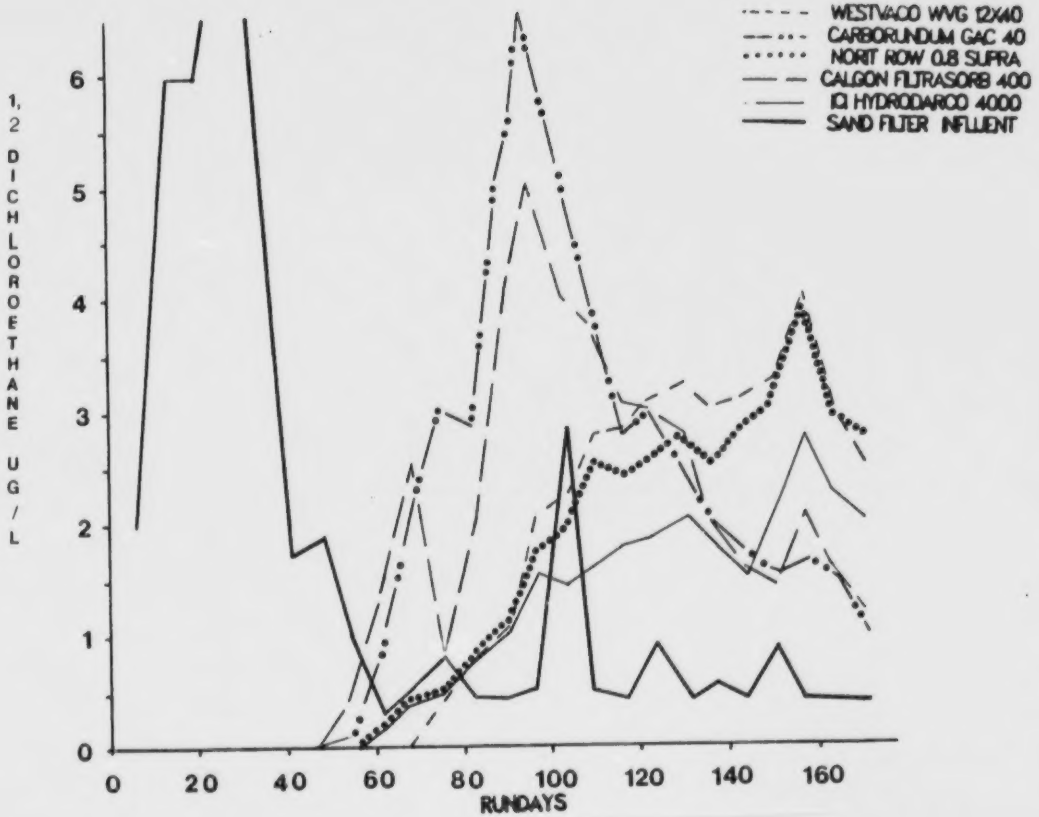

FIGURE 53. EFFLUENT 1,2-DICHLOROETHANE CONCENTRATIONS FOR EACH TYPE OF CARBON EVALUATED – JEFFERSON PARISH, LA.

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organics were evident on the flame ionization chromatograms. The chromatograms indicated the following GAC levels of contamination: Hydrodarco® > WV-G® > ROW 0.8 Supra® > GAC 40® > F400®. The degree of initial organic contamination, however, appears to have no discernable effect on adsorption as the second most contaminated GAC, WV-G®, exhibited the overall best performance.

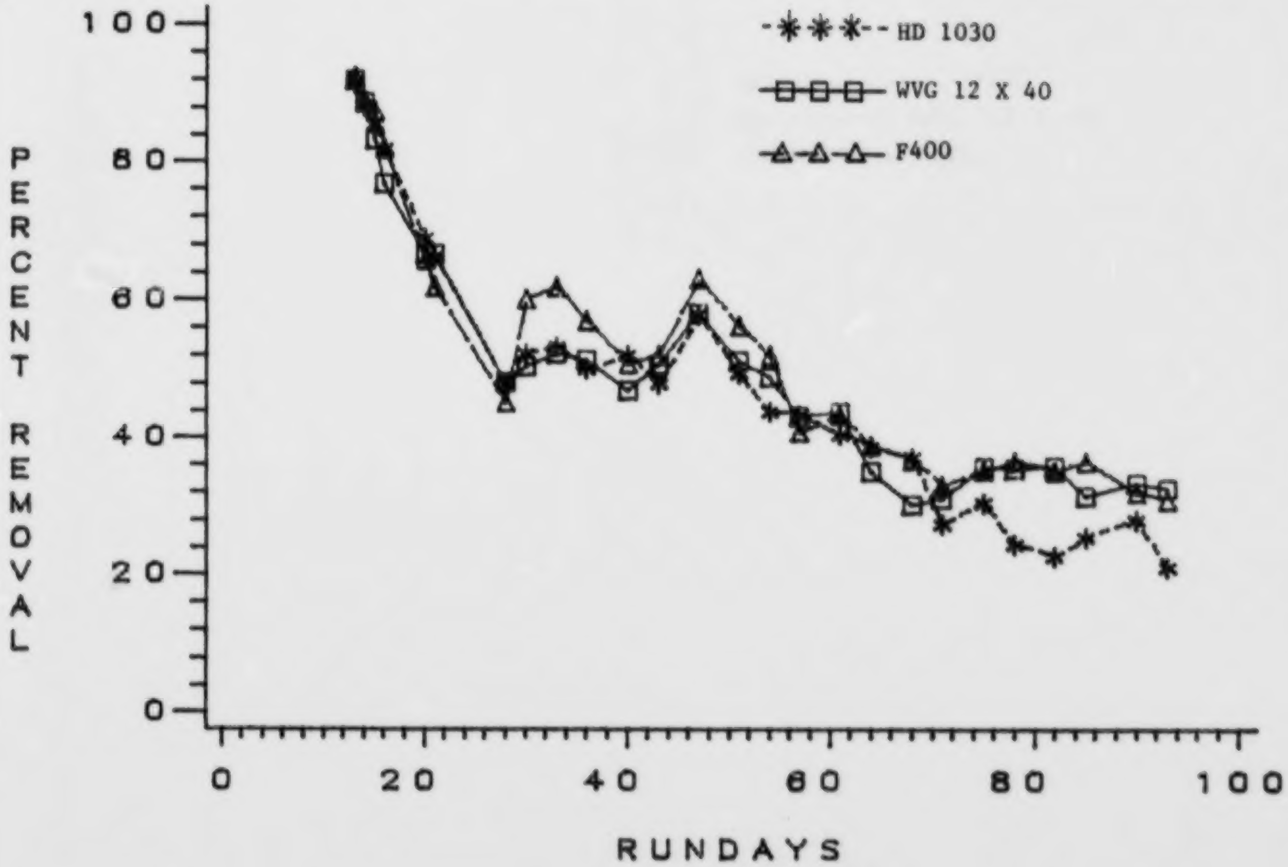
TOC removal by three carbons (HD 1030®, WVG® 12x40, and F400®) evaluated simultaneously at Passaic Valley, New Jersey showed that the performance of all three was similar. Comparison of the carbons in the virgin state (Figure 54) showed that all three removed essentially the same percent of TOC through 22 days of operation. After day 22, TOC removal with F400® was slightly better than the others.

Percentage TOC removal by once reactivated GAC at Passaic Valley was the same for F400® and WVG® 12 x 40 (Figure 55). A marked difference, however, was seen with twice reactivated GAC (Figure 56). F400® removed TOC much better than the other carbons.

Heavy Metals In GAC

The possibility of heavy metals leaching from GAC continues to be raised although previous studies have shown that a problem does not exist.(14) Under stress conditions, such as acid refluxing metals are extracted from GAC. Directo, Chen, and Miele(15) refluxed 25 grams of Calgon F300® for 24 hours with 6N HCl and rinsed with distilled water. Concentrations of metals found are shown in Table 27. Another type of GAC (WVG® 12 x 40) was digested with nitric acid which also yielded high concentrations of heavy metals(13).

Under normal operating conditions during water treatment, no heavy metals were detected leaching from GAC. Effluent concentrations from two parallel columns containing virgin HD® 10 x 30 were comparable to concentrations applied to the same GAC at Evansville, Indiana (Table 28)(6). Average GAC effluent concentrations for iron and manganese during 93 days of operation at Passaic Valley, New Jersey for HD® 10 x 30, WVG® 12 x 40, and F400® were (0.02, 0.03), (0.02, 0.02), and (0.02, 0.02) mg/L, respectively, for influent concentrations of 0.03 mg/L iron and 0.04 mg/L manganese.



BED VOLUME = 180 X RUNDAY

FIGURE 54. PERCENT TOC REMOVAL FOR VIRGIN GAC – PASSAIC VALLEY, NEW JERSEY

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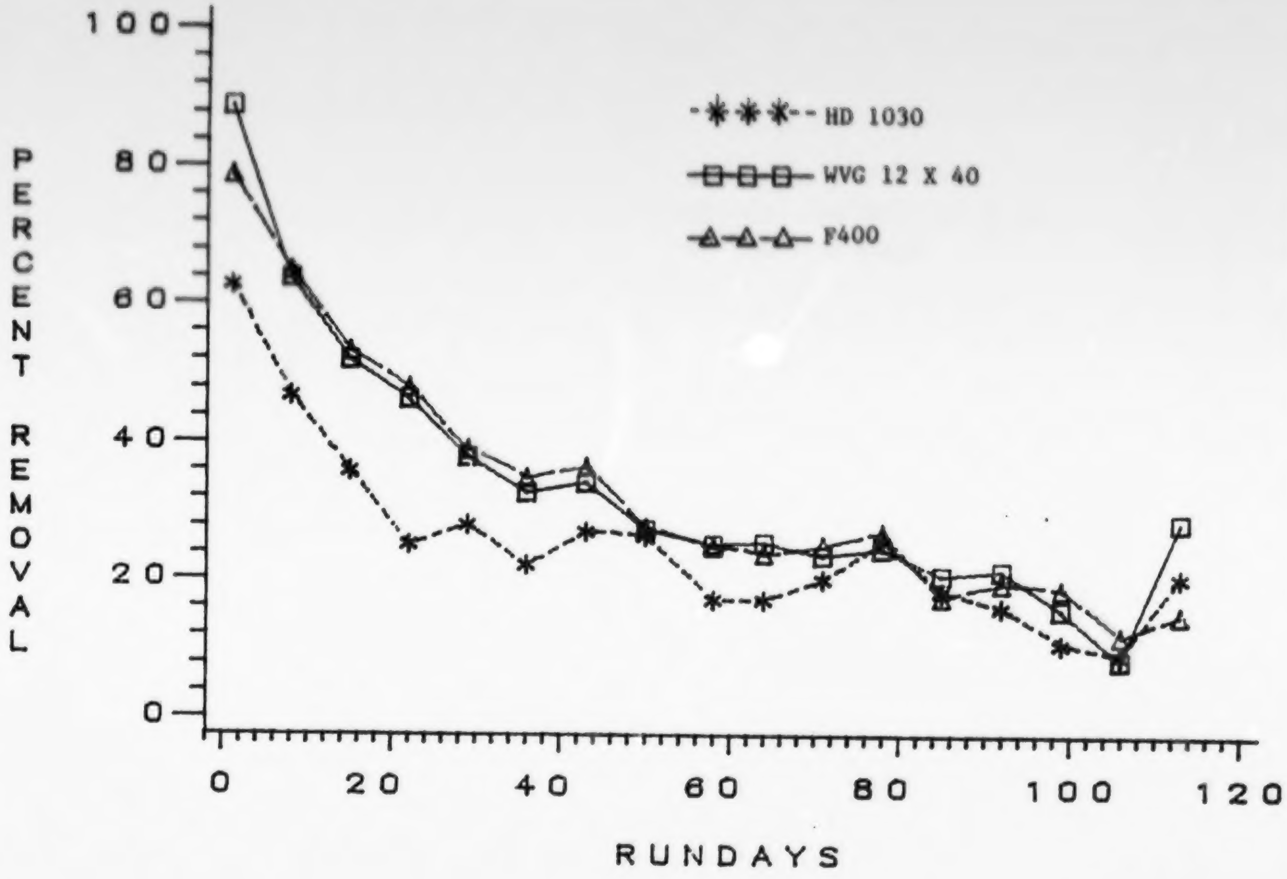
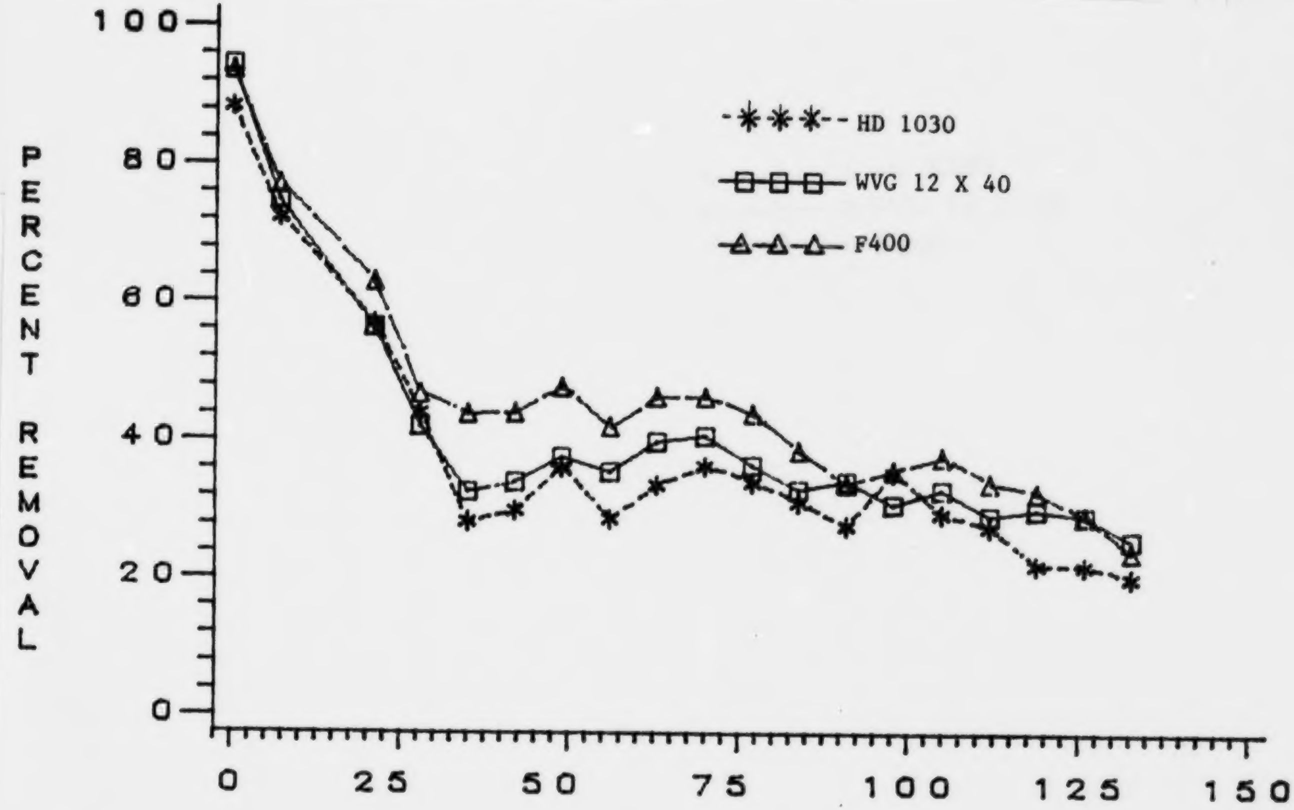


BED VOLUME = 180 X RUNDAY

FIGURE 55. PERCENT TOC REMOVAL FOR ONCE REACTIVATED GAC – PASSAIC VALLEY, NEW JERSEY



BED VOLUME = 180 X RUNDAY

FIGURE 56. PERCENT TOC REMOVAL FOR TWICE REACTIVATED GAC – PASSAIC VALLEY, NEW JERSEY

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TABLE 27. HEAVY METALS FROM VIRGIN GRANULAR ACTIVATED CARBON AFTER ACID DIGESTION

Metal	(mg/kg carbon) Filtrasorb 300[(1)]	WVG 12x40[(2)]
Ag	NA	BD
Al	1,536.	2,421.
As	108.	3.5
Ba	50.4	54.5
Be	2.4	1.2
Bi	BD	NA
Ca	391.	NA
Cd	1.2	BD
Co	BD	NA
Cr	7.2	2.7
Cu	BD	5.6
Fe	671.	3,361.
Hg	1.9	0.2
K	NA	133.
Mg	NA	144.
Mn	26.4	7.8
Mo	BD	NA
Na	NA	425.
Ni	12.	6.3
Pb	16.8	BD
Sb	BD	NA
Se	BD	BD
Sn	BD	BD
Sr	72.	BD
Ti	240.	NA
Tl	BD	NA
Zn	1.2	2.4
V	24.	BD

(1) 25g of GAC digested with HCl

(2) 0.1g of GAC digested with HNO_3

NA - not analyzed
BD - below detection

TABLE 28. CONCENTRATION OF METALS IN GAC EFFLUENTS DURING PILOT PLANT STUDY AT EVANSVILLE, INDIANA

(mg/L)

Metal	GAC Influent	GAC Effluent(1)	GAC Effluent(2)
Arsenic	< 0.001	< 0.001	< 0.001
Barium	< 0.02	0.12	< 0.02
Cadmium	< 0.003	< 0.003	< 0.003
Chromium	< 0.002	< 0.002	< 0.002
Iron	0.02	0.10	0.10
Lead	0.04	< 0.02	0.08
Manganese	< 0.1	< 0.1	< 0.1
Mercury	< 0.0008	< 0.0008	< 0.0008
Selenium	< 0.0005	< 0.0005	< 0.0005
Silver	< 0.003	< 0.003	< 0.003

(1) Virgin GAC effluent. Contactor contained virgin GAC for all runs.

(2) Virgin GAC effluent. Contactor contained virgin GAC for first run and subsequent reactivated GAC for following runs.

SECTION VI

GAC REACTIVATION

Furnace Description

GAC was reactivated on-site at three field locations (Cincinnati, Manchester, and Passaic) and off-site at one other location (Evansville). Two different types of units were used to accomplish the reactivations: fluidized bed and infrared.

Cincinnati and Manchester used a 227 kg (500 lb) per hour fluidized bed process (Figure 57). The furnace is divided into four temperature zones consisting of drying, incineration, reactivation and combustion. Dimensions of the furnace are 6.7 m (22.5 feet) tall and 2.1 m (7 feet) in diameter at its widest point. The 0.6 cm (0.25 in) outer steel shell is covered with a cast-in-place refractory lining up to 0.36 m (14 in) thickness.

Spent GAC was hydraulically educted into a storage tank where the carbon was metered through a rotary valve to a dewatering feed screw. Dewatered GAC (50% moisture) was dried in the drying zone at approximately 150°C (300°F). Dried GAC passed from the drying zone through a discharge pipe and rotary metering valve to the reactivation zone of the furnace. Temperature within the reactivation zone typically averaged about 816°C (1500°F).

In the reactivation zone, part of the adsorbate was volatilized from the GAC while the remaining pyrolyzed portion was removed by selective reaction with steam to form hydrogen and carbon monoxide. The adsorbate was pyrolyzed in the incineration zone directly above the reactivation bed. Excess gas from incineration was bypassed and mixed with off-gas from the dryer with the system gas treated in a three-stage venturi type scrubber and water tray scrubber to remove particulate matter before discharge.

The combustion chamber (bottom section of furnace) utilized a balanced mixture of fuel and oxygen to control the quality of combustion gases in the fluidizing medium. Steam was also injected into this chamber to provide an additional flow of fluidizing gases and to temper combustion chamber temperatures. The combustion chamber temperature was about 1038°C (1900°F). Reactivated GAC was discharged to a quench tank where it was cooled before eduction to the reactivated GAC storage tank.

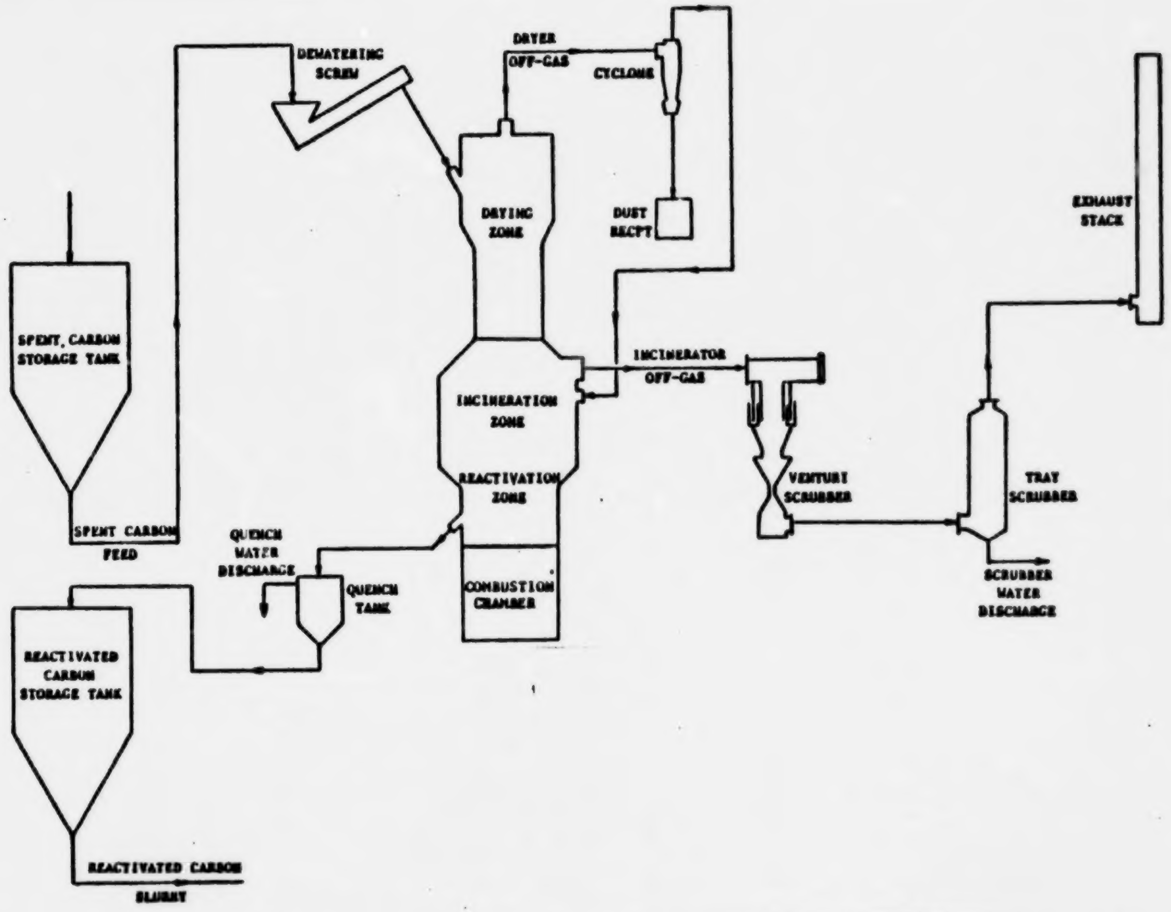
DEWATERING SCREW
DRYER OFF-GAS
CYCLONE
DUST RECPT
EXHAUST STACK
SPENT, CARBON STORAGE TANK
DRYING ZONE
INCINERATION ZONE
INCINERATOR OFF-GAS
REACTIVATION ZONE
VENTURI SCRUBBER
TRAY SCRUBBER
SPENT CARBON FEED
QUENCH WATER DISCHARGE
QUENCH TANK
COMBUSTION CHAMBER
SCRUBBER WATER DISCHARGE
REACTIVATED CARBON STORAGE TANK
REACTIVATED CARBON SLURRY

FIGURE 57. SCHEMATIC OF FLUIDIZED BED FURNACE AT CINCINNATI, OHIO

The infrared furnace was used on-site at Passaic and off-site at Evansville for reactivation of the spent GAC (Figure 58). This 45.4 kg (100 lb) per hour unit was 1.2 m (4 ft) wide by 6.1 m (20 ft) long. The GAC was dewatered during conveyance to the furnance to approximately 50 percent moisture. At the furnace, it dropped onto a woven wire conveyor belt and was leveled into a layer approximately 1.9 cm (3/4 in) thick. The conveyor belt moved the GAC underneath infrared heating elements that provided the energy necessary to dry the carbon, drive off adsorbed compounds, and restore pore structure.

Process temperatures were controlled in zones and typically ranged from 649°C (1200°F) in the drying zone to about 899°C (1650°F) in the reactivation zone. The furnace exhaust temperature was about 649°C (1200°F) and the wet-scrubbed exhaust gases discharged to the atmosphere ran about 38°C (100°F). Residence time of the GAC in the furnace was from twenty to thirty minutes.

GAC Property Measurements

As an indication that proper reactivation of spent GAC had occurred, several GAC properties were evaluated. One of the easier properties to determine that is widely accepted as an immediate indication of the efficiency of the reactivation process was the apparent density.(16) Data for this property for both furnace types show that the spent GAC was essentially restored to the virgin state (Table 29).

TABLE 29. APPARENT DENSITY OF REACTIVATED GAC

		Subsequent Reactivations			
Furnace Type	Virgin GAC (g/mL)	1 (g/mL)	2 (g/mL)	3 (g/mL)	4 (g/mL)
Fluidized bed					
Cincinnati, OH(1)	0.48	0.48	0.47	0.47	0.52
Manchester, NH(2)	0.61	0.59	0.58	0.56	-
Infrared					
Evansville, IN(3)	0.43	0.45	0.40	0.44	-
Passaic, NJ					
WVW® 12x40	0.58	0.57	0.58	0.59	
F400®	0.47	0.49	0.49	0.50	
HD® 10x30	0.44	0.43	0.43	0.43	

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(1) WVG® 12 x 40
(2) WVW® 8 x 30
(3) HD® 10 x 30

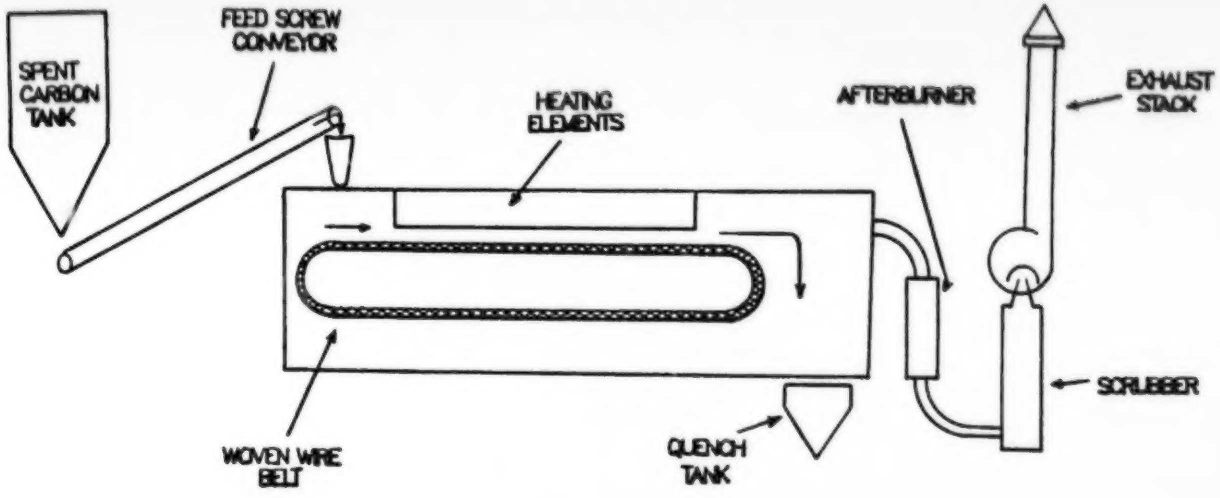
SPENT CARBON TANK
FEED SCREW CONVEYOR
HEATING ELEMENTS
AFTERBURNER
EXHAUST STACK
SCRUBBER
WOVEN WIRE BELT
QUENCH TANK

FIGURE 58. SCHEMATIC OF INFRARED FURNACE FOR GAC REACTIVATION

The general apparent density trend for the fluidized bed and infrared furnace was comparable values for subsequent reactivations when compared to the virgin GAC. A more vigorous method is used to reactivate the GAC in the fluidized bed furnace than in the infrared furnace leading to a concern that reduced apparent density and mean particle diameter may occur. If this reduction occurs, filtration rates are effected by increased filter head loss and possible media loss during backwashing. Establishing the proper conditions for reactivation is essential to remove the adsorbate but not damage the original GAC pore structure. An example of the effect on the mean particle diameter during subsequent reactivations for both furnace types is shown in Table 30. These data show that the mean particle diameter was reduced regardless of furnace type.

TABLE 30. MEAN PARTICLE DIAMATER OF SUBSEQUENT REACTIVATED GAC

Furnace Type	Virgin GAC (mm)	Subsequent Reactivations 1 (mm)	2 (mm)	3 (mm)	4 (mm)
Fluidized Bed					
Cincinnati, OH(1)	1.25	1.18	0.95	0.86	1.02
Manchester, NH(2)	1.42	1.37	1.38	1.24	-
Infrared					
Evansville, IN(3)	1.29	1.14	1.12	0.94	-

---

(1)WVG® 12 x 40
(2)WVW® 8 x 30
(3)HD® 10 x 30

Other properties seem to follow the same pattern whereby subsequently reactivated GAC was essentially restored to a state that was somewhat different than the original virgin carbon. This, however, does not mean that the reactivated GAC performed less efficiently than the virgin GAC. In many cases, the opposite was observed as will be shown later in the report. Any indication of gradual degradation of adsorptive capacity after subsequent reactivations can be shown by a correlation of the cumulative surface area and iodine number. A ratio of about one indicates that the GAC pores were opened and maintained.(17) These ratios are presented in Table 31 and show that the Cincinnati and Evansville reactivations indicate an unlikelihood of any adsorptive capacity degradation.

TABLE 31. BET SURFACE AREA/IODINE NUMBER RATIO OF SUBSEQUENT REACTIVATED GAC

		Subsequent Reactivations			
Furnace Type	Virgin GAC	1	2	3	4
Fluidized Bed					
Cincinnati, OH(1)	0.93	1.01	1.01	0.96	0.89
Manchester, NH(2)	0.99	0.90	0.78	0.70	-
Infrared					
Evansville, IN(3)	1.08	1.06	1.08	1.03	-

---

(1) WVG® 12 x 40
(2) WVW® 8 x 30
(3) HD® 10 x 30

GAC Operational Losses

From an economic standpoint, the most important GAC operational criteria to consider is carbon losses resulting from reactivation and transport. There have been two basic methods used in determining GAC losses. One method was mass balance or percent loss by weight and the other one was volumetric or percent loss by volume. The mass balance measurements were questionable because of the difficulty in accounting for losses attributed to carbon burnoff in the reactivator and during backwashing. Also, assumptions had to be made to account for bulk density differences and particle size changes.

Therefore, the volumetric method of measuring GAC losses was used. As a matter of practice, water utilities are primarily concerned with the volumetric levels of GAC in filter operation and not the particular masses.

In order to characterize the losses around the reactivation system three different measured losses were determined on the fluidized unit (filter to filter, reactivation only, and transport) and two on the infrared unit (filter to filter and reactivation). Transport losses were determined by subtraction. Several measurements were taken during each of many reactivation cycles. The average of these losses for contactors and filters containing GAC only (no sand) are shown in Table 32. Because of the measurement techniques that had to be used, some data fluctuations were noted and the outliers were discarded.

TABLE 32. AVERAGE PERCENT GAC LOSSES, BY VOLUME

Furnace Type	Transport	Reactivation	Total
Fluidized Bed			
Cincinnati, OH(1)	3.1	12.2	15.3
Manchester, NH(2)	2.0	10.9	12.9
Infrared			
Evansville, IN(3)	3.0	5.0	8.0

---

(1)WVG® 12 x 40
(2)WVW® 8 x 30
(3)HD® 10 x 30

At the Cincinnati location, GAC on a sand base was also evaluated. Total losses for this mode of operation were higher than for GAC only (18.5 percent vs. 15.3 percent). Although a sand separator placed before the furnace removed most of the sand some did enter the furnace causing less than optimum furnace operation. This problem, along with longer transport, GAC removal by shovel, and sand base inconsistency caused the losses to be greater.

Reactivation Furnace Discharge

Because various organic compounds are adsorbed by the GAC, there is a concern about the possible discharge of these organics or other organics formed within the furnace. At the time of the research projects reported in this document, services for approved stack sampling and organic analyses were difficult to obtain. During the Cincinnati study, an analysis for methane equivalent was obtained for the stack discharge. How this parameter related to specific organic compounds is unclear although the Southwest Ohio Air Pollution Authority stated that the emission quality was acceptable. A summary of the off-gas analyses for Cincinnati is presented in Table 33.

TABLE 33. SUMMARY OF AVERAGE DATA FOR REACTIVATION FURNACE STACK ANALYSES, CINCINNATI, OHIO

	GAC Contactor	GAC Filter
Particulate	g/hr (lb/hr)	g/hr (lb/hr)
Filterable	4.5 (0.01)	4.5 (0.01)
Condensable	19.5 (0.04)	13.6 (0.03)
Methane Equivalent(1)	131.7 (0.29)	81.7 (0.18)
Nitrogen Oxide	163.4 (0.36)	202.5 (0.45)

---

(1) Total gaseous non-methane organics is expressed as methane (CH_4) equivalent.

After the original GAC research effort was completed at Cincinnati, another evaluation of the GAC furnace discharge was initiated. This evaluation was to determine if tetrachlorodibenzo-p-dioxins (TCDDs) or tetrachlorodibenzo furans (TCDFs) were present in any of the furnace effluent streams.(18) The effluent streams sampled included the following:

(1) Stack exhaust (gases and particulate) after passing through the Venturi and tray scrubbers.

(2) Carbon fines removed from the drying zone off-gas by the cyclone.

(3) Combined liquid discharge from the Venturi and tray scrubbers.

(4) Overflow water from the reactivated GAC quench tank.

(5) Spent GAC feed to the reactivation unit.

The GAC used for this study had been in service for about one year and was stored in the contactor for about six months before reactivation. As shown in Tables 34 and 35, TCDDs and TCDFs were detected in low concentrations. In about all cases, the TCDDs and TCDFs were attached to the particulate material. Comparison of TCDD concentrations detected to acceptable emission discharges from municipal waste combusters shows that the GAC reactivation stack discharge was on the order of a magnitude less.(19)

The health concern for this type of discharge was addressed in an EPA document(19) that stated "present estimates of potential TCDD emission from municipal waste combusters suggest that such releases do not present a public health hazard for residents living in the vicinity of the plants." A risk assessment of the reactivation furnace stack emission discharge at Cincinnati stated that there was no evidience of a health concern. This risk assessment was done using a worst case situation of an individual at the point of maximum annual concentration, exposed 24 hours per day for 70 years, under the worst atmospheric conditions.(20)

TABLE 34. AVERAGE CONCENTRATIONS OF TCDD IN CINCINNATI, OHIO GAC REACTIVATION SAMPLES

Sample	2,3,7,8 TCDD(1)	TOTAL TCDD(1)
Spent GAC Feed, ng/g (ppb)	<0.05 (<0.05)	<0.1 (<0.1)
Cyclone Catch, ng/g (ppb)	<0.04 (<0.04)	2.21 (2.21)
Scrubber Liquid, ng/L (ppt)	0.03 (0.03)	0.08 (0.08)
Quench Water, ng/L (ppt)	<0.05 (<0.05)	<0.1 (<0.1)
Stack Gas, ng/dscm (ppt)		
Particulate Contribution	0.10 (0.08)	0.16 (0.13)
Volatile Contribution	<0.01 (<0.01)	0.02 (0.01)

---

(1) Average of four tests

TABLE 35. AVERAGE CONCENTRATIONS OF TCDF IN CINCINNATI, OHIO GAC REACTIVATION SAMPLES

Sample	2,3,7,8 TCDF(1)	TOTAL TCDF(1)
Spent GAC Feed, ng/g (ppb)	<0.07 (<0.07)	<0.14 (<0.14)
Cyclone Catch, ng/g (ppb)	0.87 (0.87)	1.68 (1.68)
Scrubber Liquid, ng/L (ppt)	<0.05 (<0.05)	<0.1 (<0.1)
Quench Water, ng/L (ppt)	<0.06 (<0.06)	<0.12 (<0.12)
Stack Gas, ng/dscm (ppt)		
Particulate Contribution	0.08 (0.06)	0.26 (0.21)
Volatile Contribution	<0.02 (<0.02)	0.05 (0.04)

---

(1) Average of four tests

The precursors for formation of TCDDs and TCDFs at Cincinnati that are present on the carbon are unknown. Chlorinated compounds such as trichlorophenols are suspected as one of the precursors. Another possible precursor could be PCBs that are present in the natural gas used to fire the furnace. PCBs were detected in the natural gas supply at a concentration of 2.6 micrograms per standard cubic meter (2.2 ppb). The principal PCBs detected were tri- and tetrachlorobiphenyls.

In order to completely eliminate the formation of TCDDs and TCDFs, their precursors will have to be removed. PCBs in the natural gas can be removed by an adsorbent. Chlorinated precursors such as trichlorophenols need not be formed, if non-chlorine disinfectants (ozone) are used prior to carbon adsorption.

According to the literature TCDDs are destroyed at temperatures above 800°C.(21) If an afterburner temperature during GAC reactivation is maintained above 800°C with sufficient oxygen and detention time the gaseous TCDDs will probably be destroyed. The challange, however, is not to form them in the first place.

Although the raw water source at Manchester did not contain identifiable specific organic contaminants, a test was conducted on the GAC furnace stack emission to see if certain organic species may be formed in the furnace. At the time of this sampling, the question of TCDD and TCDF formation in the furnace had not been raised. Also, no one seemed to know what organic compounds to expect in the stack discharge. Therefore, the samples collected at Manchester were analyzed for the following compounds because the contractor was experienced in stack sampling and analysis and recommended these compounds.

methylene chloride
1,1 dichloroethylene
bromochloromethane
chloroform
1,2 dichloroethane
1,1,1 trichloroethane
carbon tetrachloride
bromodichloromethane
1,2 dichloropropane
1,1,2 trichloroethane

Only chloroform was detected in the gaseous stack sample at low concentrations (<12 ppb). Particulate emissions were well below the New Hampshire standard.

Reactivation Furnace Operation

The infrared furnace manufacturer has claimed ease of operation with quick start-up and shut-down capabilities. Because an extensive evaluation of its operation has not been done, these claims are not endorsed or refuted. A complete evaluation of its operation will be done during the second Jefferson Parish, LA research project.(22) There have been, however, some indications of various problems. These include belt stretching, lamp breakage, 304 stainless steel components deteriorating, and inconsistent leveling of GAC on the belt.

An extensive evaluation was done of the fluidized bed furnace at two locations (Cincinnati, OH and Manchester, NH). There were numerous problems with maintaining furnace operation. Some of these problems were relative to operator training and lack of a sufficient spare parts inventory and some were caused by inherent deficiencies in construction of the furnace. By implementing steps to improve operation and correcting major deficiences, furnace uptime was improved from a low of 30 percent to about 80 percent.

This information is presented so that the reader is aware that the reactivation furnace operation can be labor and time intensive. Proper operator training is a must with operational efficency improving with experience.

Virgin vs Reactivated GAC

As mentioned previously, spent virgin GAC was subsequently reactivated during research at four project sites: on-site at Cincinnati, Manchester and Passaic, and off-site at Evansville. Although two different furnace types were used (fluidized bed at Cincinnati and Manchester and infrared at Passaic and for Evansville), the same performance criteria were used; namely return the GAC back to essentially virgin state as determined by its properties.

The ideal approach for determining the effects of reactivation is to determine the absorbent performance of subsequently reactivated to virgin GAC using parallel systems so that the same influent is applied to both. This was only possible in Evansville with the other locations evaluating their systems at different periods of time with GAC influent variations such as temperature, water quality, etc. When looking at performance, however, percent removal and organic loading was used for comparative purposes to normalize the varying influent concentrations and GAC weights.

For consistency, only post treatment adsorbers are compared. In Cincinnati, the TOC influent concentration varied from 1.8 to 2.6 mg/L. Virgin GAC received 1.9 mg/L TOC and once and twice reactivated GAC 2.6 and 1.8 mg/L, respectively. A comparison of the percent TOC removal in Figure 59 shows that all systems from virgin through twice reactived GAC performed essentially the same (within 15 percent) for up to 60 days of operation. The loading on these GAC systems is shown in Figure 60 also indicating that the three systems were comparable (one hundred percent removal would produce a 45 degree slope).

The closeness of the GAC performance was also reflective in the GAC properties as shown in Table 36. With the molasses number increasing and the BET surface area decreasing, indications are that the pore structure has been changed to reflect the destruction of smaller pores with the creation of larger pores. This change, however, did not seem to effect the performance of the GAC for TOC removal and only slightly changed the mean particle diameter.

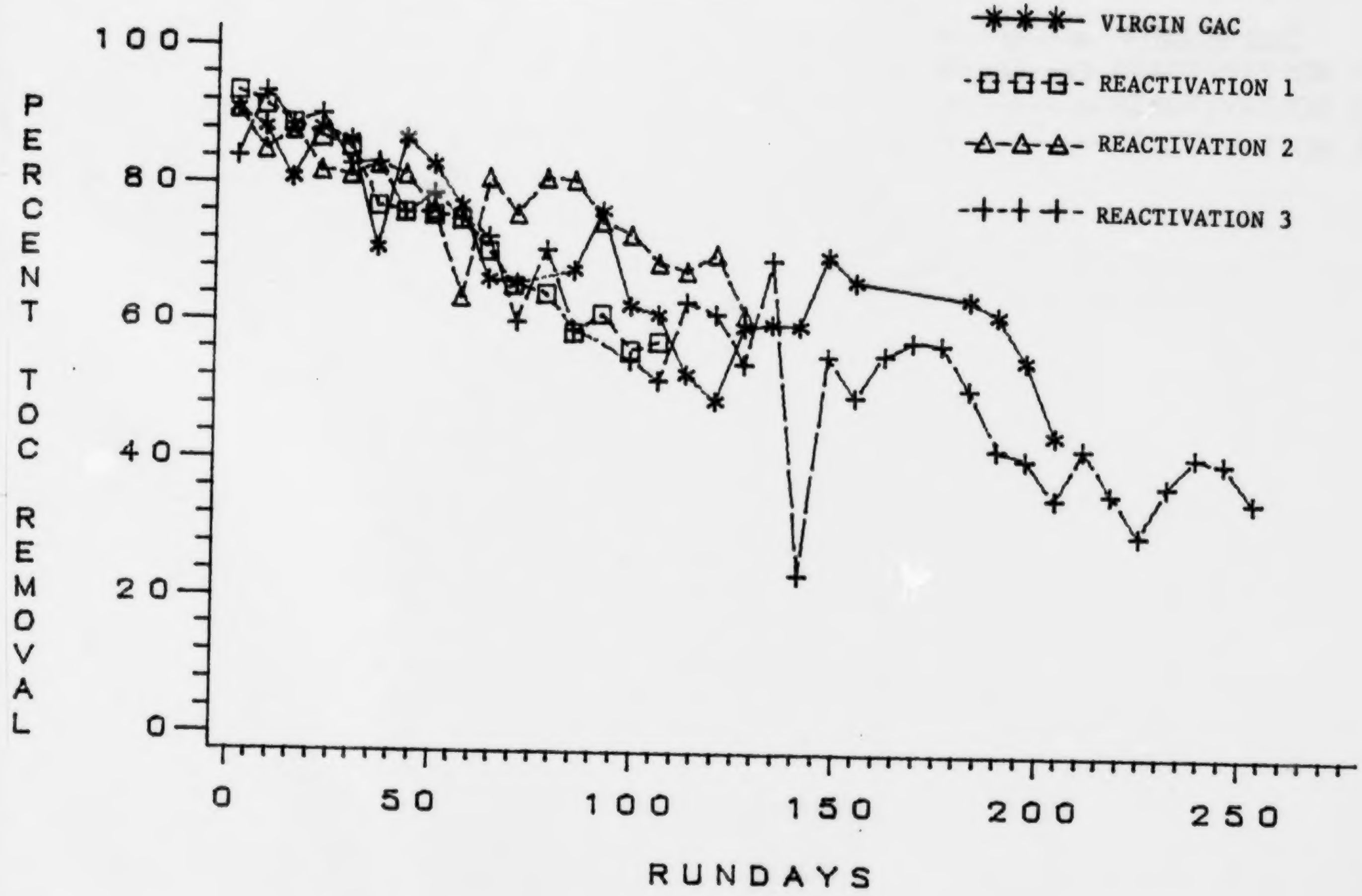

FIGURE 59. TOC PERCENT REMOVAL FOR MULTIPLE RUNS OF POST TREATMENT ADSORBERS – CINCINNATI, OHIO

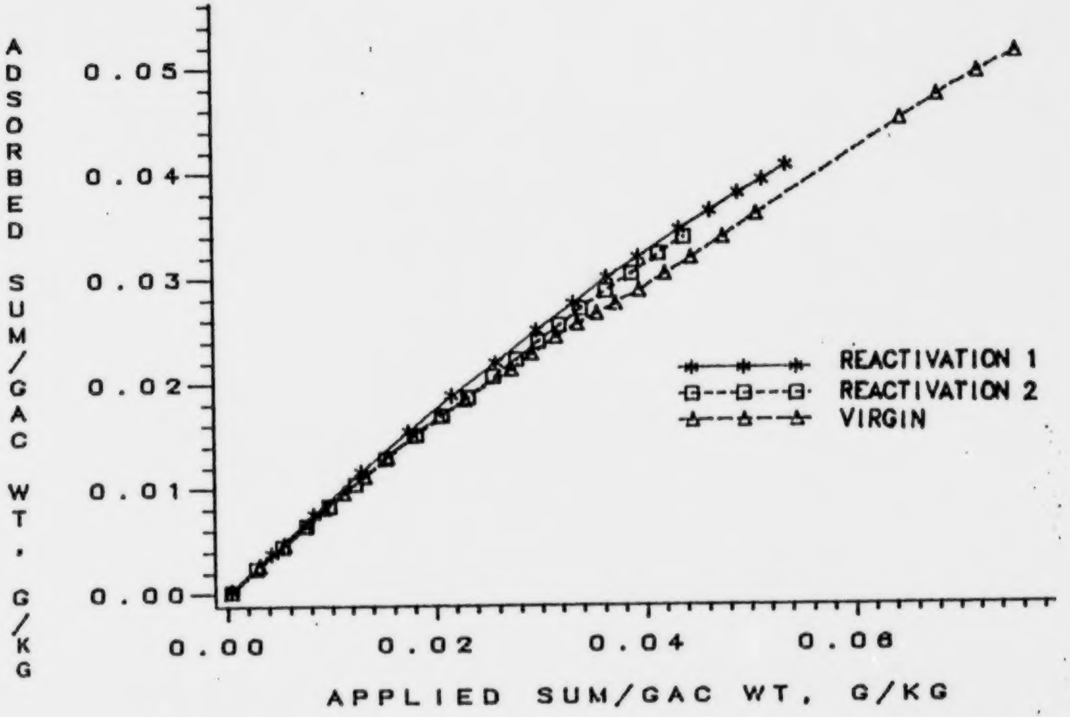

FIGURE 60. TOC ADSORBED PER GAC WEIGHT FOR MULTIPLE RUNS OF POST TREATMENT ADSORBERS, CINCINNATI, OHIO

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(PREVIOUSLY CIN- EPA FORM 387)
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TABLE 36. COMPARISON OF PROPERTIES FOR SUBSEQUENT REACTIVATED POST ADSORPTION GAC AT CINCINNATI, OHIO

GAC State	Iodine No. (mg/gm)	BET Surface Area (sq m/gm)	Molasses No. (DIU)(1)	Apparent Density (gm/mL)	Particle Diameter (mm)
Virgin	1128	1070	9.6	0.506	1.10
Once Reactivated	1030	1046	10.7	0.508	1.04
Twice Reactivated	1096	1013	12.6	0.495	1.02

(1)Decolorizing Index Unit

At Manchester, the spent virgin GAC was subsequently reactivated twice. With each reactivation, this carbon appeared to improve in performance as shown by the loading curves in Figure 61. This performance improvement, however, seems to have been produced by over reactivation of the GAC as indicated by an increase in the iodine number. Furnace conditions for reactivation of the GAC were determined by the quickest method possible (apparent density). Because of the inherent inaccuracies of this test furnace conditions were not always appropriately established. Table 37 shows the GAC property changes with each reactivation. Of special note is the increase in iodine number and BET surface area with a corresponding drop in apparent density. The mean particle diameter remained essentially the same although it would have been expected to decrease.

TABLE 37. PROPERTIES FOR VIRGIN AND SUBSEQUENTLY REACTIVATED GAC AT MANCHESTER, NH

GAC State	Iodine No. (mg/gm)	BET Surface Area (sq m/gm)	Molasses No. (DIU)(1)	Apparent Density (gm/mL)	Particle Diameter (mm)
Virgin	795	789	3.2	0.614	1.40
Once Reactivated	970	816	5.2	0.596	1.30
Twice Reactivated	1203	892	4.4	0.573	1.40

(1)Decolorizing Index Unit

With less vigorous reactivation at Passaic (infrared furnace), all three types of GACs evaluated showed that the virgin GAC performed better than the subsequently reactivated GACs as indicated by the TOC performance curves (Figure 62). Although the properties are different for the various GACs, Table 38 shows that these properties are essentially restored to those of virgin carbon.

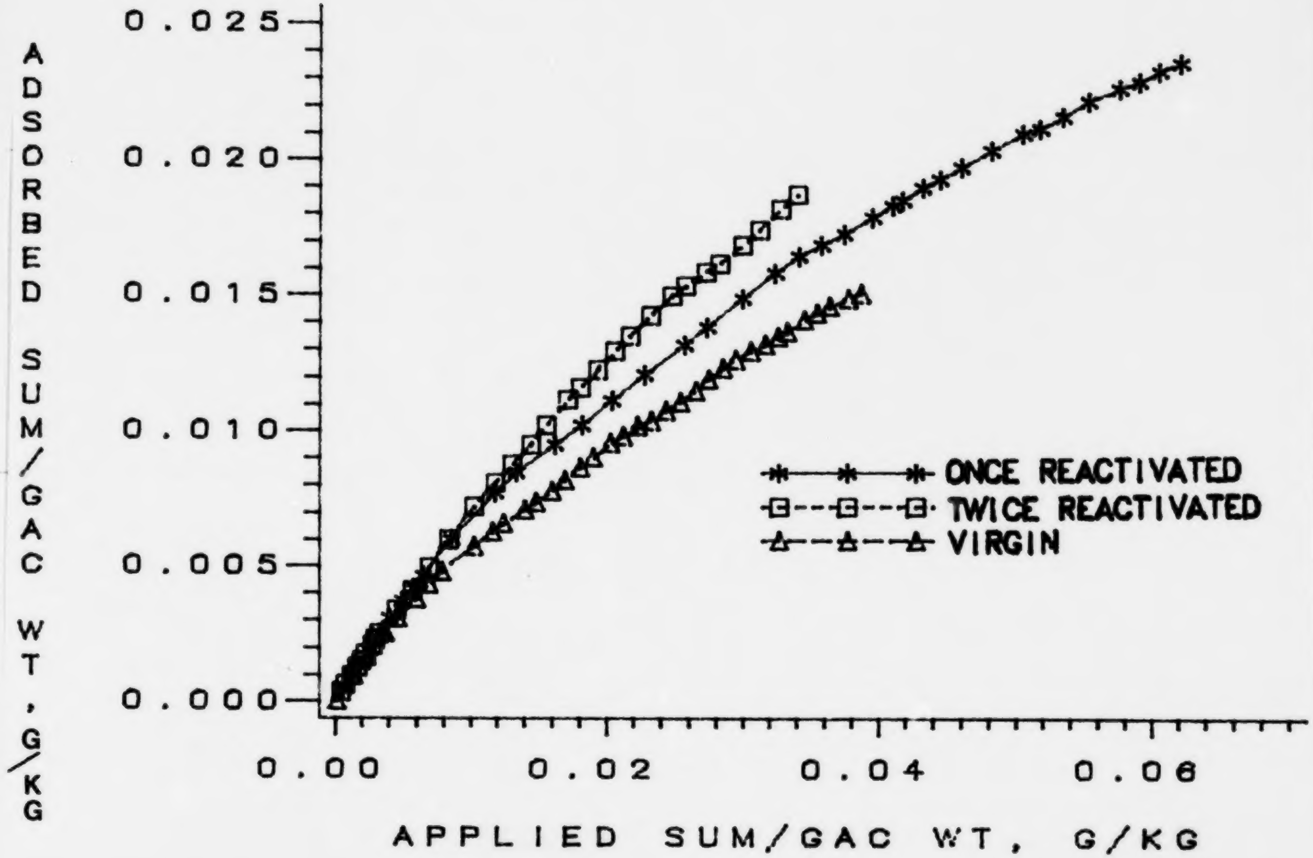

FIGURE 61. TOC LOADING ON VIRGIN AND SUBSEQUENT REACTIVATED GAC – MANCHESTER, NH

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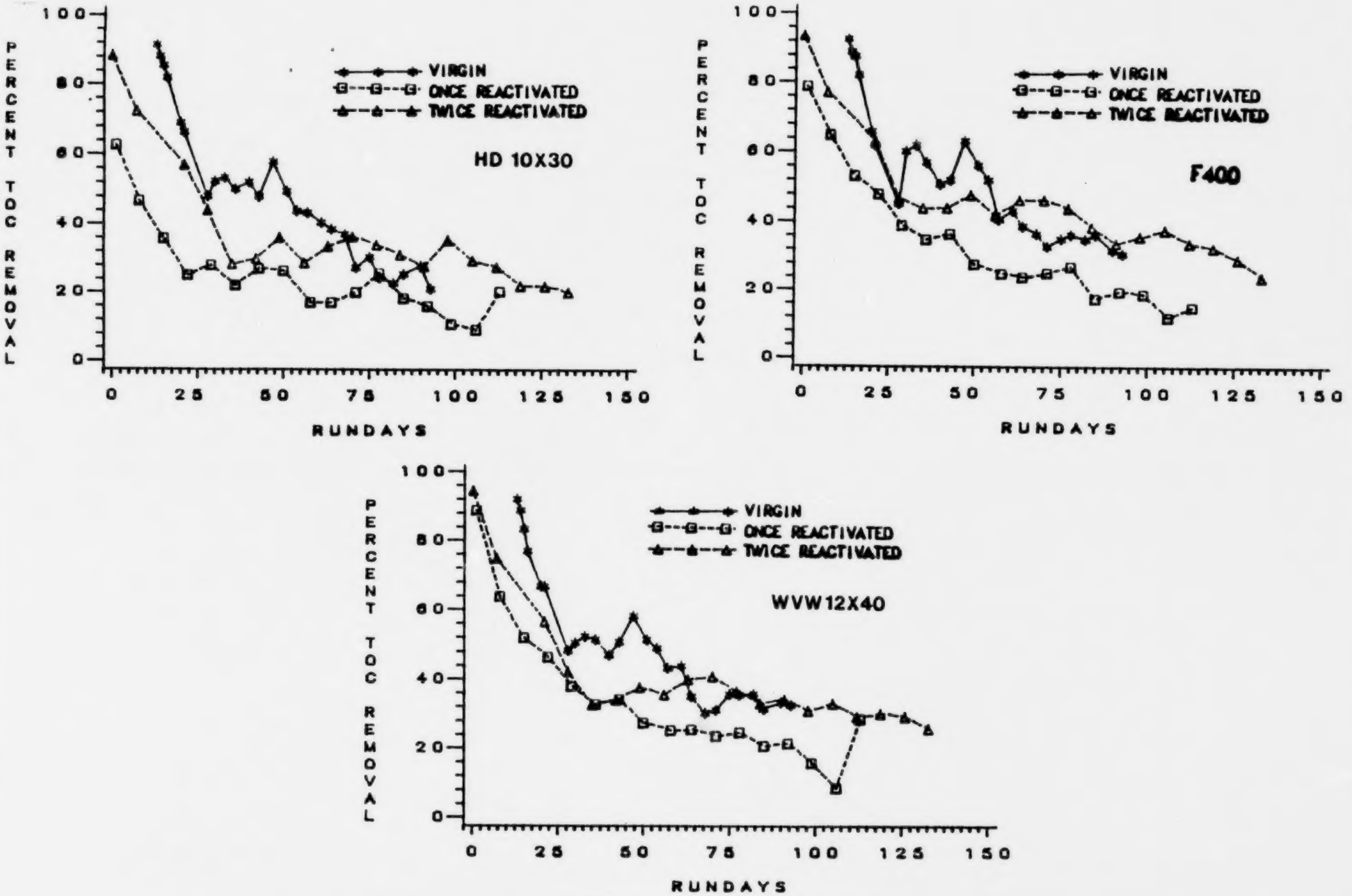

FIGURE 62. TOC REMOVAL AT PASSAIC, NJ

TABLE 38. PROPERTIES FOR VIRGIN AND SUBSEQUENTLY REACTIVATED GAC AT PASSAIC VALLEY, NJ

GAC State	Iodine No. (mg/gm)	Apparent Density (gm/mL)	Effective Size (mm)
HD® 10x30			
Virgin	488	0.42	0.86
Once Reactivated	581	0.42	0.78
Twice Reactivated	617	0.42	0.72
F400®			
Virgin	890	0.49	0.74
Once Reactivated	923	0.49	0.75
Twice Reactivated	882	0.51	0.67
WVW® 12x40			
Virgin	761	0.57	0.76
Once Reactivated	807	0.58	0.71
Twice Reactivated	758	0.59	0.64

At Evansville the same influent water was applied to two contactors. One always contained virgin GAC and the other subsequently reactivated GAC. Figure 63 shows that for three reactivations the carbon in both contactors removed TOC essentially the same with the reactivated GAC removing slightly more than the virgin GAC. TOC loading on the two systems was also about the same for each reactivation with slightly more adsorbed by the reactivated GAC (Figures 64 and 65).

A trend appeared to develop for the iodine number and molasses decolorizing index with the data showing that the spent GAC was restored to essentially virgin state. The iodine number increased from 617 to 650 mg/gm and the decolorizing index decreased from 18.5 to 13.7 (Table 39). The iodine number and cumulative surface area correlated almost exactly indicating that the pores were opened and maintained so that there was an unlikelihood of any gradual degradation of adsorptive capacity after subsequent reactivations. The ratios for BET Surface Area/Iodine Number for an average of virgin GAC and three subsequent reactivations were 1.08, 1.06, 1.08, and 1.03, respectively.

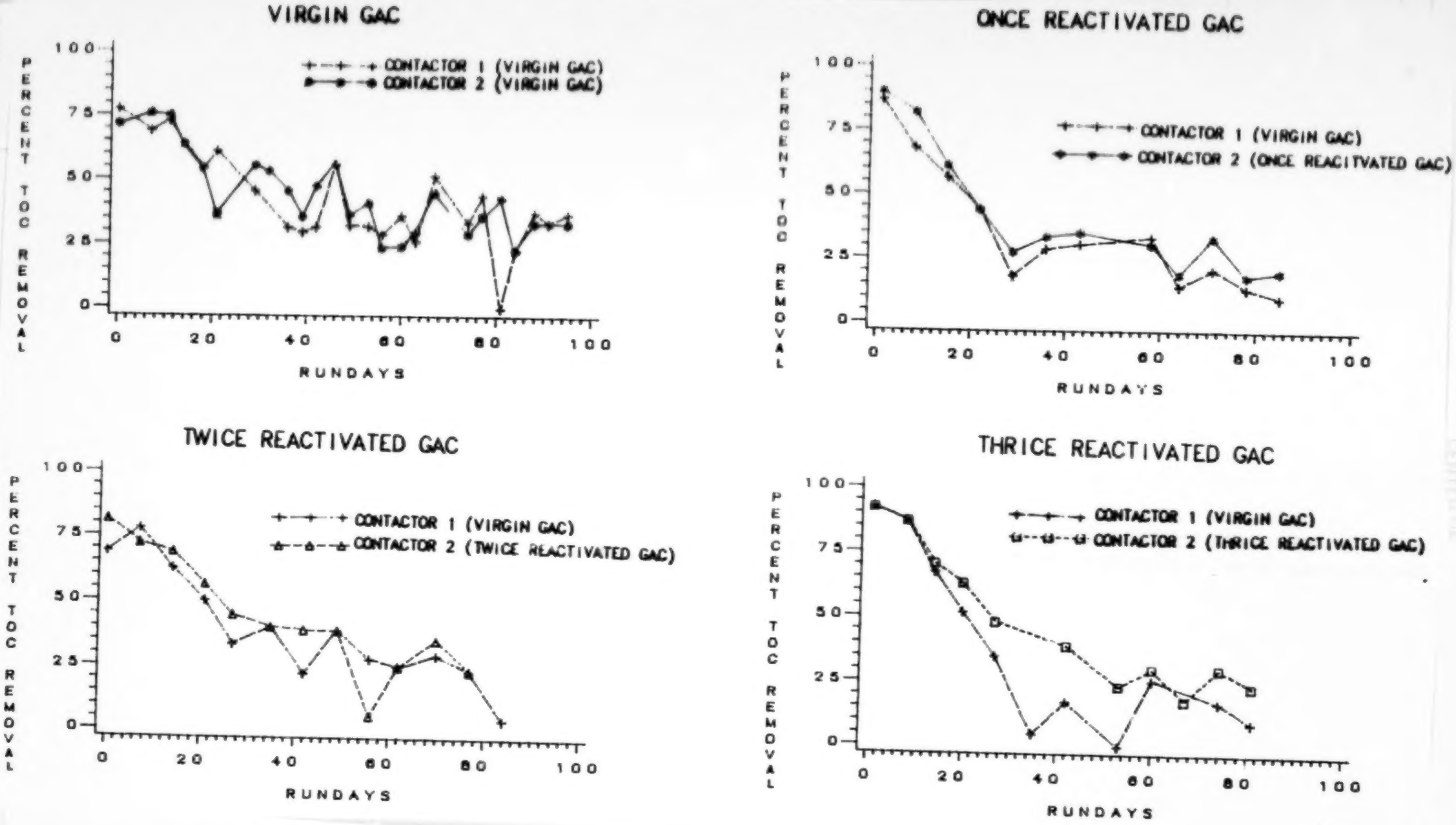

FIGURE 63. TOC REMOVAL AT EVANSVILLE, IND.

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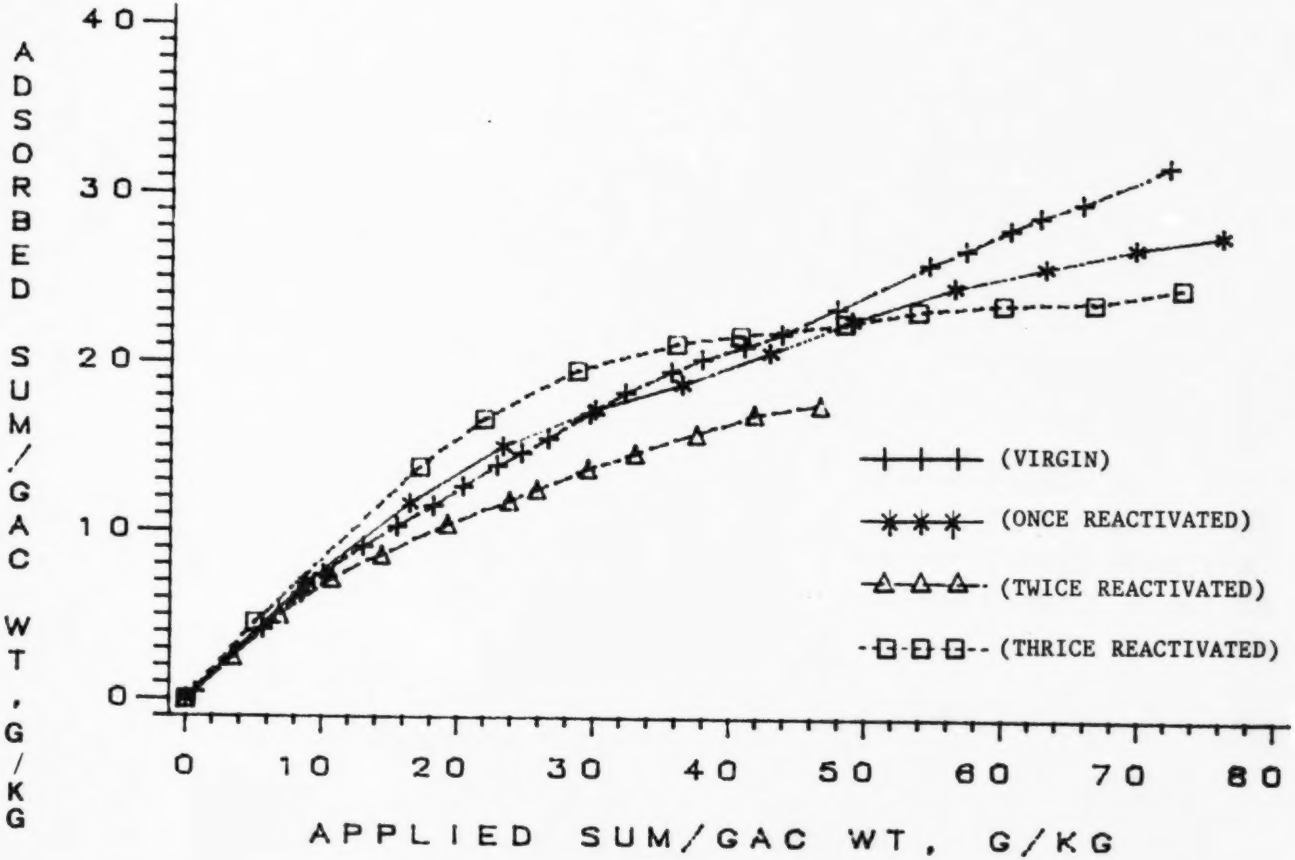

FIGURE 64. TOC LOADING FOR VIRGIN GAC DURING EACH RUN (CONTACTOR 1) – EVANSVILLE, IND.

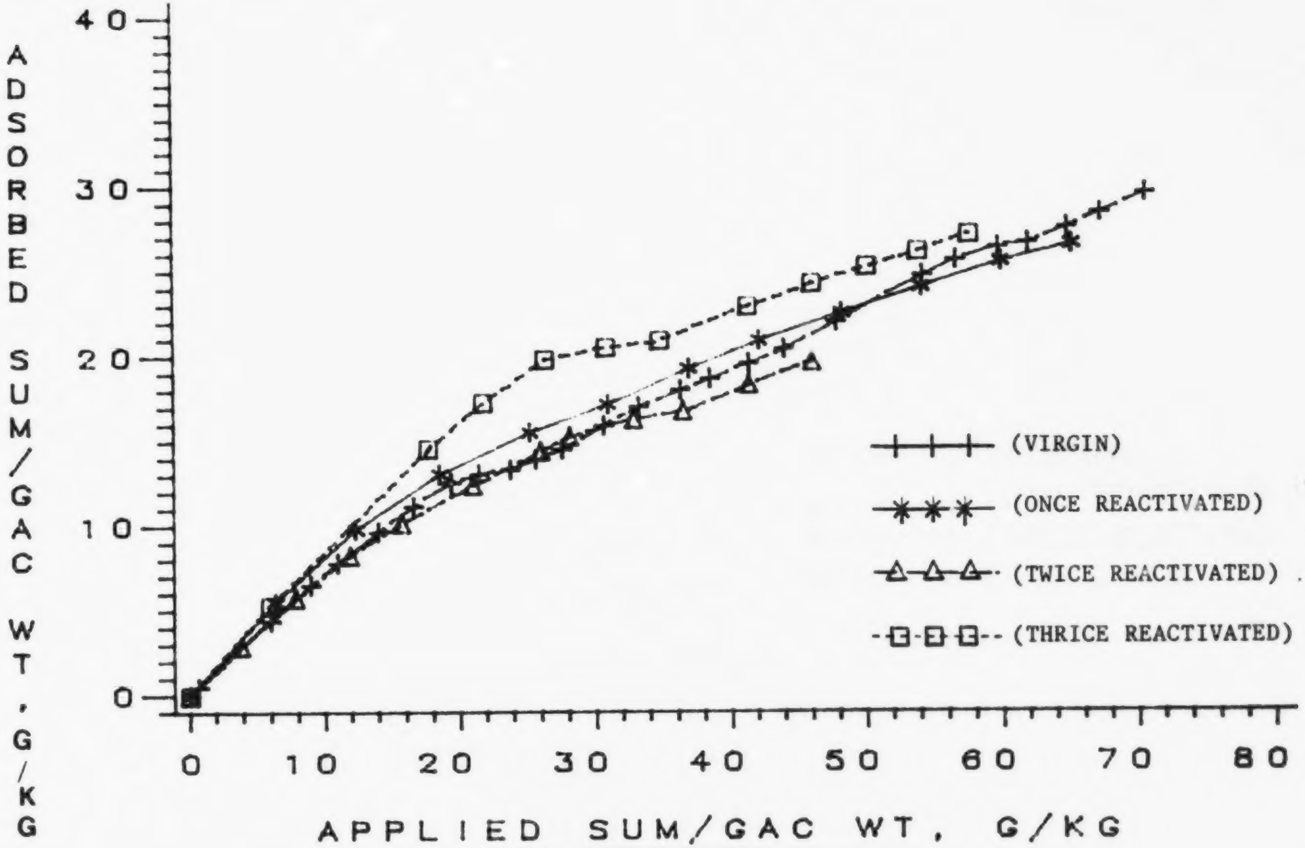

FIGURE 65. TOC LOADING FOR SUBSEQUENTLY REACTIVATED GAC DURING EACH RUN (CONTACTOR 2) – EVANSVILLE, IND.

TABLE 39. PROPERTIES FOR VIRGIN AND SUBSEQUENTLY REACTIVATED GAC AT EVANSVILLE, INDIANA

GAC State	Iodine No. (mg/gm)	BET Surface Area (sq. m/gm)	Molasses No. (DIU)(1)	Apparent Density (gm/mL)	Particle Diameter (mm)
Virgin	617	597	18.5	0.427	1.29
Once Reactivated	638	675	17.8	0.447	1.14
Twice Reactivated	596	644	14.7	0.403	1.12
Thrice Reactivated	650	688	13.7	0.440	0.94

(1) Decolorizing Index Unit

SECTION VII

SUMMARY OF GAC PERFORMANCE

GAC has been in use for many years to remove taste and odors in drinking water(23). Within the past ten years, some utilities have seriously considered the use of GAC for removal of trace organics from their drinking water. With more sophisticated instrumentation rapidly becoming available that is affordable and useable by utilities, more organics at trace levels are being detected. Utility managers as well as the general public are becoming more concerned about the health effects of ingesting trace levels of various organics over many years.

This concern has caused the Cincinnati Water Works to proceed with full-scale implementation of GAC adsorption. Other utilities have indicated an interest in GAC as funding becomes available. Major waterways such as the Ohio and Mississippi contain many hundreds of trace organics in the parts per trillion range. Because of its broad spectrum adsorbent capability, GAC is the preferred method for removing most of these organics.

The performance of GAC has been evaluated at several field locations. In some of the locations comprehensive cost data have also been collected. Many specific organics were monitored but only a few were detected consistently. The general parameter of TOC was used in many cases to determine the performance of GAC. By removing TOC through GAC adsorption, one can be reasonably sure that most of the specific organics are being removed. This is the case although TOC concentrations are in mg/L and the total concentration of the specific organics equals only a few hundred ug/L. Therefore, an undefined organic fraction is also removed by GAC.

Various GACs produced for organics removal were evaluated. Generally, the coal base GACs resulted in the best removals over a longer time period. Of the carbons evaluated, WVG 12 x 40 coal base GAC appeared to be a better choice for removal of low molecular weight volatile organics such as 1,2-dichloroethane. The higher molecular weight organics appeared to be equally well removed by all of the coal base GACs evaluated.

Using steady-state TOC as an evaluation criterion, three months would generally be expected to be the service life of GAC before replacement or reactivation. Deviations both greater than and less than three months have been seen. High TOC/organic precursor waters can generally expect shorter GAC service times before exhaustion whereas other water sources have experienced more than three months GAC operation before exhaustion.

Direct GAC adsorption after coagulation/settling appears to produce comparable water quality as that from post sand filtration adsorption with the same EBCT. Water utilities without the capital or available land can replace their sand with GAC and effectively remove turbidity and organics if sufficient EBCT is available. If, however, a utility has a choice of filtration/adsorption or post-sand filtration adsorption, the latter would be recommended. Sand filtration prvides another barrier for certain microbial contaminants (24). Also, turbidity accumulation on the GAC will require more frequent backwashing.

Both GAC pilot columns and pilot plants can be used to predict the performance of a full-scale system. EBCT is important for efficient GAC operation but longer is not necessarily cost-effective. For each situation, there is an optimum EBCT after which a diminishing return can be expected. Generally, from the sites evaluated, 15 to 25 minutes EBCT is optimum based on a steady-state TOC removal.

GAC has been effectively reactivated. Performance of subsequently reactivated GAC is comparable if not better than virgin GAC. Thermal reactivations do produce volume losses, ranging from 5 to 12 percent depending on the furnace type. Within the infrared furnace, approximately 5 percent losses can be expected. Ten to twelve percent losses can be expected from the fluidized-bed furnace. An additional 3 percent loss can also be expected for carbon transport regardless of furnace type.

There is always a concern that organics in water adsorbed on GAC will be transferred to the air during reactivation. The intent during GAC reactivation is to incinerate the adsorbate. During GAC reactivation, however, some organics have been detected in the stack gases. The detected organics of major concern are TCDD and TCDF. Although both total TCDD and TCDF concentrations were in the low ppt range (0.14 ppt TCDD and 0.25 ppt TCDF) there is a concern that any concentration was detected. A major portion (0.13 ppt TCDD and 0.21 ppt TCDF) of the levels found were attached to the particulates in the stack gas.

When a dispersion model was applied to the stack discharge, no health hazard was indicated. There is, however, a concern about disposal of carbon fines that contain higher concentrations (4.1 ppb total TCDD and 3.3 ppb total TCDF). TCDDs and TCDFs are produced during reactivation from precursor compounds. Some of these precursors are suspected of being formed during chlorination and they can possibly be controlled by using a non-halogenated disinfectant prior to GAC adsorption. Other control measures include thermal destruction of the TCDDs and TCDFs after formation.

SECTION VIII

MICROBIAL CONCERNS WITH GAC TREATMENT PROCESSES

Selection of treatment strategies for organic removal in drinking water should recognize the potential consequences of microbial actions in process modifications. Primary among these considerations are microbial colonization and periodic releases of increased bacterial densities which must be controlled by final disinfection prior to release into the distribution system.

Surface waters may not only receive a variety of organic pollutants from upstream industrial waste discharges but also carry numerous pathogenic bacteria released via ineffective sewage treatment processes. In addition, watersheds may often receive significant levels of pesticides and fecal pollution from various agricultural pursuits. Furthermore, wildlife over the area will provide a continuous low density residual of fecal bacteria that cannot be ignored. These sources of pollution introduce a wide range of infectious agents to water resources that may ultimately be found in water supply.

The more common infectious agents in contaminated water may be classified within four broad groups: bacteria, viruses, protozoans and helminths and are derived from infected humans and other warm-blooded animals. Other agents of concern include fungi, viroids and toxins. Although some infectious agents cannot survive outside their host for any great length of time, control in water supply treatment is normally provided through a series of multiple barriers to microbial survival.

Turbidity in raw source water and that created in water treatment processes must be minimized because this material may protect microorganisms present and facilitate their safe passage into the finished water. Particulates in surface waters are introduced through stormwater runoff over the watershed, in the destratification of raw water impoundments, seasonal algal blooms, chemical spills upstream and natural siltation processes. Ground waters may acquire turbidity from intrusions of leachates originating in nearby landfills, pollutional waste injections that penetrate the aquifier, dissolution of minerals by aeration and microbial slime releases from colonization of the well casing or water bearing sand. Particulates may also result from poor water treatment practices. For instance, poor settling of coagulants, particle breakthrough in sand or diatomaceous filters and inadvertent release of carbon fines from treatment operational practices that include dual media filters, carbon capped sand filters and GAC contactors (adsorbers) can be sources of some particulates that enter the distribution system. Nematode infestations of filter beds may be another source of particulates that enter the finished water and provide protection from disinfection contact through bacterial ingestion with later discharge of viable cells into the potable water supply.

Treatment strategies to remove organics from raw source water must therefore not create a pathway for the passage of pathogens into the finished water. Since there are a variety of treatment configurations using granular activated carbon that will remove varying amounts of raw water organics, this section will evaluate available data from six research full scale operations and pilot plant investigations of GAC treatment as it affects the microbial quality of process water, finished water and drinking water in distribution.

GAC Characteristics

A variety of carbon materials have been used to produce the adsorption surfaces essential to organic removals. Carbon sources include bituminous coal, bones, coconut shells, lignite, peat, pecan shells, petroleum based residues, pulp mill black ash, and wood.(25) Materials used in the full scale and pilot plant studies described in this report were predominantly coal base or lignite (Table 40). While particle size between various granular activated carbons were fairly uniform (based on seive sizing), surface areas for adsorption and microbial attachment were more related to source of GAC material. Apparently, lignite derived GAC had approximately 60 percent of the total surface area as that of GAC produced from coal. Regardless of the carbon source, the activation processes include treatment with an oxidizing gas (steam or air) at high temperatures. Variations in adsorption capacity do occur among commercial supplies of GAC and are related largely to both carbon source material and the activation process employed by the manufacturer. Other key characteristics include GAC particle pore structure, total surface area, void spaces between particles and hydrophobicity.(26) Many of these characteristics are also of importance in establishment of microbial colonization of the GAC filter bed. For this reason, the persistence and growth of organisms of public health concern (primary pathogens, opportunistic pathogens and indicators) in GAC filters have drawn considerable attention in recent years.(1,28,29)

TABLE 40. CHARACTERISTICS OF GRANULAR ACTIVATED CARBONS

Manufacturer	Trade Name	Source Material	Sieve Size	Surface Area (m^2/g)
Calgon	Filtrasorb C	Coal	12X40	----
Calgon	Filtrasorb 400	Coal	12X40	1050-1200
Carborundum	GAC 40	Coal	12X40	1000-1100
ICI	Hydrodarco 1030	Lignite	10X30	600
Westvaco	WVW 8X30	Coal	8X30	800
Westvaco	WVW 14X40	Coal	14X40	±940
Westvaco	WVG 12X40	Coal	12X40	1050-1100

Sanitary Quality of Virgin Carbon

Start up operations using GAC material in several pilot plant and full scale processes revealed a surprising initial coliform and heterotrophic bacterial contamination problem. The origin of this contamination may have been either from the filter basin converted from sand filtration operation, the GAC supplied by the manufacturer or in the water slurry movement of GAC into the filter compartment.

Full scale evaluation of three different types of GAC placed into converted sand filter basins (Table 41) illustrates the possibility that these basins were not adequately cleaned prior to conversion. Initial influent quality for the first two months to each of these new GAC beds brought no detectable total coliforms in 100 ml samples and contained a free-chlorine residual of 1.0 to 2.0 mg/L. However, filter effluent water from each of the three different GAC materials (Filtrasorb 400, Filtrasorb C and Hydrodarco 8X16) contained 46 to 85 total coliforms per 100 ml during the first week run. On both Filtrasorb materials, total coliform densities peaked in three weeks then declined to less than one coliform per 100 ml by week 13 or 14. Hydrodarco GAC prepared from lignite did not exhibit any increase of coliforms above the start up density of 46 total coliforms per 100 ml in the effluent and proceeded to decline to below detectable levels by week eleven. The heterotophic bacterial population rose to density levels of 10^4 per ml within 4 to 5 weeks then declined below 10^2 organisms per ml by the eleventh week for both Filtrasorb materials. Microbial growth on the Hydrodarco material peaked at 10^4 organisms per ml during week seven then declined to below 10^2 organisms per ml by the eleventh week paralleling similar microbial activity on the other two GAC materials. These findings suggest that available nutrients and declining water temperatures were important factors in microbial persistence in the GAC contamination problem.

Lignite (Hydrodarco 1030) and bituminous (WVW 12X40) materials were also evaluated in pilot contactor columns to determine what effects faster water flow and an enclosed structure would have on microbial colonization. Four pilot contactor columns were constructed to hold 0.9-1.2 m (3-4 ft) of lignite or bituminous material over a support base of gravel that was 10.2 cm (4 in) thick for the lignite or layered 5.8 cm (2.3 in) at the bottom of columns packed with bituminous material.

Effluent water from the plant sand filters was passed under pressure through each set of four columns connected in series. Bacteriological data (Table 42) was obtained for the GAC influent (sand filter effluent) and both sets of GAC effluents over a 168 day period. Influent water contained few heterotrophic bacteria (SPC per ml) but there were density increases of 100 to 1000 more bacteria discharged in the GAC effluents. The highest densities occurred initially in the lignite effluent during the decline in seasonal water temperatures. This condition suggested that the lignite, gravel or column walls were initially contaminated and required approximately one month of water passage to dilute the bacterial discharges in the effluent. Bacterial releases from bituminous material ranged from 97 to 510 organisms per ml through the study period. No coliforms were ever detected in either the influent water or two GAC effluents.

TABLE 41. COMPARATIVE STUDY OF THREE GAC PRODUCTS IN FULL SCALE FILTRATION AT THE BEAVER FALLS, PA., MUNICIPAL AUTHORITY

Testing Interval Week	GAC influent						GAC effluent**											
							Filtrasorb® 400				Filtrasorb® C*				HD 8x16			
	Water Temp. °C	Residual chlorine, mg/L Free	Residual chlorine, mg/L Total	Turbidity, ntu	Total coliforms/ 100 mL	Standard plate count/ mL	Residual chlorine, mg/L Free	Residual chlorine, mg/L Total	Total coliforms/ 100 mL	Standard plate count/ mL	Residual chlorine, mg/L Free	Residual chlorine, mg/L Total	Total coliforms/ 100 mL	Standard plate count/ mL	Residual chlorine, mg/L Free	Residual chlorine, mg/L Total	Total coliforms/ 100 mL	Standard plate count/ mL
1	21	2.0	†	5.6	<1	†	0	0	64	†	0	0	85	†	0	0	46	†
2	21	1.7	1.7	4.8	<1	†	0	0	75	†	0	0	95	†	0	0	25	†
3	15	1.3	1.4	2.3	<1	†	0	0	98	1,000	0	0	130	740	0	0	33	1,700
4	11	1.1	1.3	2.9	<1	100	0	0	45	1,400	0	0	50	60,000	0	0	23	1,100
5	16	1.2	1.4	2.5	<1	800	0	0	34	25,000	0	0	28	42,000	0	0	12	3,800
6	16	1.4	1.6	3.3	<1	350	§	<0.1	42	2,000	§	<0.1	12	40,000	0.1	0.2	13	3,000
7	16	1.1	1.2	3.6	<1	10	§	<0.1	28	20,000	§	<0.1	12	52,000	§	<0.1	2	45,000
8	10	1.0	1.0	3.2	<1	42	§	<0.1	22	29,000	§	<0.1	21	32,000	§	<0.1	8	92,000
9	10	1.3	1.6	4.6	2	110	§	§	13	6,500	§	<0.1	7	6,500	§	<0.1	2	21,000
10	8	1.0	1.3	4.5	<1	33	§	<0.1	12	1,600	§	<0.1	18	1,800	§	<0.1	5	1,800
11	6	1.4	1.6	3.7	<1	95	§	<0.1	2	960	§	<0.1	1	820	§	<0.1	1	900
12	3	1.0	1.1	5.9	1	360	§	<0.1	1	270	§	<0.1	2	380	§	<0.1	<1	320
13	4	1.2	1.7	4.6	<1	660	§	<0.1	<1	480	§	<0.1	1	540	§	<0.1	<1	380
14	2	1.3	1.5	6.6	1	200	§	§	1	440	§	<0.1	<1	110	§	<0.1	<1	200
15	1	1.0	1.2	4.8	<1	120	§	<0.1	<1	44	§	<0.1	<1	50	§	<0.1	<1	74
17	1	1.4	1.7	5.9	<1	150	§	<0.1	<1	50	§	<0.1	<1	16	§	0.1	<1	26
18	1	1.0	1.1	5.5	<1	33	§	<0.1	<1	21	§	<0.1	<1	20	§	<0.1	<1	9
22	1	0.4	1.6	6.4	<1	30	§	0.3	<1	30	§	0.4	<1	23	<0.1	0.4	<1	47
23	4	0.3	1.6	5.8	<1	24	§	0.4	<1	13	§	0.2	<1	10	§	0.4	<1	15
25	4	§	1.4	6.6	<1	38	§	0.2	<1	21	§	0.2	<1	35	§	0.2	<1	24
27	7	†	1.4	6.3	<1	58	†	0.1	<1	41	†	0.1	<1	27	†	0.2	<1	10
29	10	0.2	1.1	1.7	<1	33	†	0.1	<1	31	†	0.1	<1	28	†	0.3	<1	17
32	11	0.2	1.6	1.9	<1	17	†	0.3	<1	69	†	0.2	1	82	†	0.3	<1	19

*Not commercially available.
†Not run.
§Trace.
**Turbidity in the three GAC media effluents was below 1 ntu.

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TABLE 42. MICROBIAL QUALITY OF EFFLUENTS FROM LIGNITE AND BITUMINOUS MATERIALS IN PILOT COLUMNS*

Testing Interval	Influent Quality			Lignite (Hydrodarco 1030)			Bituminous (WVW 12X40)		
Week	°C	Turbidity	SPC/ml	Turbidity	SPC/ml	Total Coliforms per 100 ml	Total Turbidity	SPC/ml	Total Coliforms per 100 ml
1	9.5	0.3	27	0.2	2,000	< 1	0.1	140	< 1
7	8.0	0.3	3	0.1	2,400	< 1	0.1	130	< 1
14	7.2	0.1	-	0.1	-	-	0.1	-	-
16	-	-	3	-	2,200	< 1	-	130	< 1
21	6.5			0.1	5,100	-	0.1	280	-
28	5.1	0.2	< 1	0.1	420	< 1	0.1	260	< 1
35	3.2	0.6	1	0.2	460	< 1	0.1	70	< 1
42	2.8	0.3	< 1	0.1	560	< 1	0.1	240	< 1
49	3.8	0.1	4	0.1	600	< 1	0.1	290	< 1
56	2.8	0.2	< 1	0.1	320	< 1	1.0	190	< 1
63	4.7	0.1	< 1	0.2	910	< 1	0.1	400	< 1
70	1.7	0.2	-	0.1	-	-	0.1	-	-
72	-	-	< 1	-	< 1	< 1	-	< 1	< 1
140	13.0	0.2	< 1	0.1	500	< 1	0.1	200	< 1
147	17.0	0.2	1	0.1	314	< 1	0.1	268	< 1
154	17.9	0.2	1	0.2	1,220	< 1	0.1	510	< 1
161	21.8	0.2	< 1	0.2	400	< 1	0.2	250	< 1
168	19.4	0.1	3	0.1	280	< 1	0.1	97	< 1

*Cincinnati Pilot Plant Study; December 12, 1978 to May 29, 1979

GAC Reactivation

Since the adsorption capacity of GAC is eventually exhausted after a period of a few months to several years (depending on type and concentration of organics in the process water), there is a need to either replace or reactivate the material for reuse. Reactivation generally involves passing the spent carbon through a furnace heated to 820-930°C to oxidize adsorbed materials in a controlled atmosphere. This reactivation process results in some loss of material and may cause some particle size reduction and change in surface characteristics. What effect these subtle changes in physical characteristics have on bacterial adhesion to GAC and impact, if any, from residual chemicals on microbial colonization of these reactivated particles is not known. Some insight into this aspect can be seen in data gathered from a pilot plant evaluation of virgin and reactivated carbon and a similar study at a full scale site where the GAC was cycled through three periods of use and reactivation.

Product water from the sand filters in the Cincinnati Water Treatment train was fed to parallel 0.9 m (2.6 ft) columns of either virgin carbon (WVG 12X40) or reactivated GAC of the same origin. Effluent turbidity measurements from both columns during the first 63 days were often higher than found in the influent water (sand filter effluent). Because NTU measurements do not detect carbon fines, these increased values (Table 43) represented intermittent passage of entrapped influent turbidity particles during initial stablization of the packed column.

There was more significant releases of heterotrophic bacteria in the virgin GAC once the water temperature began to rise to over 10°C than noted with the use of reactivated GAC. Perhaps the surface texture on reactivated particles was less conducive to bacterial attachment sites i.e. less open fractures in the carbon particles (change in pore size distribution) or accumulative toxic residuals were effectively limiting microbial colonization. During this warm water period, chlorine residuals were generally undetectable in these effluents. There were only infrequent coliform occurrences recorded in either column effluent during this period; one coliform per 100 ml on two occasions in virgin GAC and 1, 7, and 12 coliforms per 100 ml in three effluents from the reactivated carbon. Only on one day (June 19, 1979) was there concurrent coliform occurrences in effluents from both carbon columns. No coliforms per 100 ml were detected in any influent samples. Correlation of coliform occurrences with increased turbidity releases was inconclusive because of the limited data available based on one sample per week.

The field study of full scale operation using GAC filters provided evidence that microbial activity on virgin GAC (Westvaco WVW 8X30) and the same GAC material reactivated were identical. While water temperature above 10°C does encourage coliform regrowth, the essential element is in the bacterial quality of processed water applied to these filters. Data in Table 44 for the initial run indicates the microbial quality remained excellent during 112 days of operation. This occurred 41.2% of the time in the spring with water temperatures above 10°C. However, during the second

TABLE 43. EVALUATION OF EFFECTS OF GAC REACTIVATION ON MICROBIAL QUALITY OF EFFLUENT*

Testing Interval Day	Water Temp. °C	Turbidity (NTU)			Heterotrophic Bacteria/ml			Total Coliforms/100 ml		
		GAC Influent	GAC Effluent		GAC Influent	GAC Effluent		GAC Influent	GAC Effluent	
			Virgin	React.		Virgin	React.		Virgin	React.
1	7.9	0.1	0.4	0.1	27	57	260	1	1	< 1
7	5.5	0.3	0.1	0.1	3	20	120	< 1	< 1	1
16	-	-	1.6	12.0	-	17	180	-	< 1	< 1
21	-	-	1.0	0.4	-	28	8	-	-	-
28	3.0	0.1	2.4	2.5	4	28	25	< 1	< 1	< 1
35	1.7	0.6	2.0	0.7	1	3	31	< 1	< 1	< 1
42	1.5	0.3	1.0	1.5	< 1	16	45	< 1	< 1	< 1
49	2.2	0.1	0.8	0.6	4	57	16	< 1	< 1	< 1
56	1.0	0.2	1.3	0.2	< 1	9	59	< 1	< 1	-
63	4.0	0.1	2.1	0.4	< 1	4	73	< 1	< 1	-
141	14.5	0.2	-	-	< 1	-	-	< 1	-	-
155	19.1	0.2	0.2	0.2	1	144	220	< 1	< 1	< 1
162	21.0	0.2	0.2	0.2	< 1	4,500	460	< 1	< 1	< 1
169	19.7	0.1	0.1	0.1	3	870	84	< 1	< 1	< 1
176	19.3	-	0.1	0.2	-	1,400	36	-	< 1	< 1
183	21.5	-	0.1	0.1	-	3,200	38	-	< 1	< 1
190	23.9	-	0.5	0.4	-	400	200	-	1	7
197	23.3	-	0.2	0.2	-	-	140	-	< 1	12
204	22.4	-	0.2	0.1	-	230	78	-	-	-
211	23.5	-	0.2	0.2	-	89	41	-	< 1	< 1
218	25.3	-	0.1	0.1	-	99	42	-	< 1	< 1
225	26.6	-	0.2	0.1	-	250	250	-	-	-

*Cincinnati Pilot Plant Study, December 12, 1978-July 24, 1979

TABLE 44. EVALUATION OF EFFECTS OF REACTIVATION ON GAC EFFLUENT MICROBIAL QUALITY*

Testing Interval	Water Temp.	Turbidity (NTU)			Heterotrophic Bacteria/ml			Total Coliforms/100 ml		
		GAC	GAC Effluent		GAC	GAC Effluent		GAC	GAC Effluent	
Day	°C	Influent	Virgin	React.	Influent	Virgin	React.	Influent	Virgin	React.
GAC Once Reactivated										
1	8.2	0.4	0.3	0.4	1	-	< 1	< 1	< 1	< 1
7	6.5	0.3	-	-	< 1	< 1	1	< 1	< 1	< 1
14	8.1	0.2	0.1	0.1	1	1	3	< 1	< 1	< 1
21	8.2	0.2	0.1	0.1	< 1	< 1	< 1	< 1	< 1	< 1
28	6.5	0.1	0.1	0.1	< 1	1	< 1	< 1	< 1	< 1
35	7.5	0.2	0.1	0.1	1	< 1	1	< 1	< 1	< 1
42	6.7	0.2	0.1	0.1	< 1	< 1	< 1	< 1	< 1	< 1
49	6.8	0.2	0.1	0.1	< 1	< 1	< 1	< 1	< 1	< 1
56	8.1	0.3	0.2	0.2	< 1	< 1	< 1	< 1	< 1	< 1
63	8.6	0.3	0.2	0.2	< 1	< 1	1	< 1	< 1	< 1
70	10.4	0.2	0.2	0.1	< 1	1	1	< 1	< 1	< 1
77	11.5	0.2	0.2	0.2	1	1	< 1	< 1	< 1	< 1
84	12.5	0.2	0.2	0.2	< 1	2	< 1	< 1	< 1	< 1
91	14.3	0.3	0.3	0.3	< 1	< 1	< 1	< 1	< 1	< 1
98	15.3	0.3	0.2	0.2	< 1	< 1	< 1	< 1	< 1	< 1
105	17.2	0.3	0.2	0.2	1	1	< 1	< 1	< 1	< 1
112	18.5	0.3	0.3	0.3	1	< 1	1	< 1	< 1	< 1
GAC Twice Reactivated										
1	25.4	0.3	0.3	0.3	< 1	184	281	< 1	< 1	< 1
7	23.5	0.3	0.2	0.2	< 1	130	102	< 1	< 1	< 1
14	20.8	0.2	0.2	0.2	43	297	107	8	12	17
21	21.5	0.2	0.2	0.2	10	3	8	1	< 1	< 1
28	17.2	0.2	0.2	0.2	1	1	< 1	< 1	5	2
35	16.9	0.3	0.3	0.3	< 1	3	< 1	< 1	< 1	< 1
42	15.2	0.2	0.2	0.2	< 1	< 1	13	< 1	6	3
49	14.7	0.3	0.2	0.2	< 1	< 1	< 1	< 1	6	8
56	11.1	0.3	0.2	0.2	< 1	< 1	3	< 1	1	13
63	10.9	0.3	0.3	0.3	1	< 1	1	< 1	< 1	< 1
70	8.3	0.4	0.3	0.3	< 1	1	< 1	< 1	< 1	< 1
77	7.0	0.2	0.2	0.2	1	< 1	< 1	< 1	< 1	< 1
84	6.1	0.2	0.1	0.5	< 1	< 1	1	< 1	-	1
91	5.7	0.1	0.1	0.1	< 1	< 1	< 1	< 1	< 1	< 1
98	4.8	0.3	0.1	0.1	1	< 1	4	< 1	< 1	< 1
105	4.7	0.3	0.1	0.1	< 1	< 1	3	< 1	< 1	< 1
112	5.0	0.2	0.1	0.1	< 1	< 1	< 1	< 1	< 1	< 1

*Manchester, N.H. Full Scale Operation

run that started in early autumn, a different pattern of bacterial quality of the filter effluents was noted. GAC influent water from the sand filter was observed to contain 1 to 8 total coliforms per 100 ml in a two week period (Sept. 16 to 23, 1980). With warm water temperatures, some colonization of coliforms occurred and there was passage of these organisms through both GAC filters intermittently during a 7 to 11 week period before declining to nondetectable levels per 100 ml. Heterotrophic bacteria densities rose two weeks before coliforms were detected and declined over the same time period.

Turbidity measurements did not correlate with these bacterial quality changes in the GAC filter effluents. The succeeding run of virgin GAC in parallel with GAC reactivated a third time (data not presented) produced the same high quality effluents noted in the first run. Again the influent GAC process water was excellent. These data demonstrate that if influent water is of excellent bacteriological quality, transient microbial persistence with only minimal regrowth will result whenever some passage of organisms occurs in the pretreatment stages. Passing this high quality process influent water into either the virgin GAC or reactivated GAC filters produced similar bacteriological qualities in the filter effluents.

Pressure Contactors

While granular activated carbon is often used in conventional treatment beds designed originally for sand filtration, GAC may also be used in pressure contactors. In this latter configuration, GAC bed depth is usually more than 0.9 m (36 in) to provide sufficient contact time necessary to remove certain classes of organics as the water is pumped through each unit.

Since little information is available in the published literature on the bacteriological aspects of pressure contactors, measurements for heterotrophic bacteria and total coliforms in the effluents from these devices were included in various pilot and field scale operations. Factors to be considered were the extent of bacterial colonization in fast flowing water through a deeper GAC bed and containment in a closed cylinder. Three different virgin GAC materials (Hydrodarco 1030, WVW 12X40 and Filtrasorb 400) were evaluated simultaneously in a pilot plant. Influent water to the contactors was finished water containing 0.6 to 1.3 mg/L free chlorine residual.

Influent data (Table 45) indicated the finished water to be of high quality throughout the study period. One weakness with this interpretation was the sampling interval which was daily for the first four days and then once every 2 to 4 days thereafter. Such infrequent sampling will not recognize intermittent pulsing of low density levels of microorganisms into the pressure contactors. Coliforms were detected in the effluent from all contactors during days 1 to 4 and additionally from the Filtrasorb 400 contactor on days 24 and 63. Colonization and subsequent breakthrough was unlikely because of cold water temperatures.

TABLE 45. MICROBIAL QUALITY OF GAC CONTACTOR EFFLUENT IN PILOT PLANT STUDY ON THREE VIRGIN CARBONS*

Testing Interval Days	Water Temp. °C	Standard Plate Count/ml				Total Coliforms/100 ml			
		Influent**	HD 10X30	WVW 12X40	Calgon F-400	Influent**	HD 10X30	WVW 12X40	Calgon F-400
1	3.9	4	32	520	24	< 1	< 1	8.6	1.9
2	2.8	1	150	810	14	< 1	< 1	4.9	4.9
3	0.6	1	360	820	24	< 1	2.1	< 1	8.6
4	0.6	< 1	-	-	3	< 1	2.1	< 1	2.1
8	2.8	1	630	9,000	1	< 1	< 1	< 1	< 1
9	3.9	6	9,400	9,000	3	< 1	< 1	< 1	< 1
16	3.9	1	-	-	-	< 1	< 1	< 1	< 1
18	5.0	1	390	510	240	< 1	< 1	< 1	< 1
21	7.2	< 1	800	650	500	< 1	< 1	< 1	< 1
24	7.8	1	390	570	610	< 1	< 1	< 1	2.1
28	8.3	< 1	520	270	470	< 1	< 1	< 1	< 1
31	10.6	< 1	58	65	630	< 1	< 1	< 1	< 1
35	9.4	1	1,100	-	-	< 1	< 1	< 1	< 1
39	8.9	< 1	1,500	49	280	< 1	< 1	< 1	< 1
42	11.1	< 1	-	-	-	< 1	< 1	< 1	< 1
45	12.2	< 1	-	-	540	< 1	< 1	< 1	< 1
49	12.2	< 1	-	-	-	< 1	< 1	< 1	< 1
52	12.8	< 1	-	-	-	< 1	< 1	< 1	< 1
56	11.7	< 1	-	240	560	< 1	< 1	< 1	< 1
59	12.8	< 1	-	-	590	< 1	< 1	< 1	< 1
63	12.2	< 1	1,700	440	630	< 1	< 1	< 1	2.1
66	11.1	1	6	4	240	< 1	< 1	< 1	< 1
70	16.1	1	17	3	54	< 1	< 1	< 1	< 1
73	13.9	< 1	1,300	1	1,760	< 1	< 1	< 1	< 1
78	17.2	1	90	1	15	< 1	< 1	< 1	< 1
81	20.0	< 1	190	3	8	< 1	< 1	< 1	< 1

* Date from Passaic N.J. Pilot Plant Study.

**Influent water contained 0.6-1.3 mg/l free chlorine residual.

A study of the heterotrophic bacterial population in different systems in this report suggests some differences in density magnitudes that does not relate to water temperature, type of GAC or process utilized. These inconsistencies are a reflection on the Standard Plate Count protocol which recently has been demonstrated to detect less of the heterotrophic bacterial population than R2A medium, and use by some investigators of extended incubation time (7 days) and 28°C incubation temperature rather than 35°C.

Use of reactivated GAC (Hydrodarco 10X30) in contactors with GAC bed depth of 2.0 m (6.5 ft) was investigated in one phase of another pilot study. In this situation, the influent water was of lesser quality than the chlorinated finished water used in the Passaic study. Ohio River water was predisinfected with chlorine dioxide, chemicals added, flocculated, settled and passed through a mixed media filter to become influent water for the GAC contactors.

Virgin Hydrodarco 10X30 GAC was used for 2 months with this pilot plant water system. During this test period, heterotrophic bacterial densities increased to 3 logs of the influent within 4 days and one coliform breakthrough occurred on day 12 when 64 total coliforms and 53 total coliforms per 100 ml were detected in the influent and effluent, respectively. No coliforms were detected before or after that day, suggesting colonization was not a factor.

At termination of this 60 day run, the treatment process was discontinued, the GAC removed from the contactor and shipped to an off-site location for reactivation. Upon return, this reactivated GAC was placed in the contactor and the testing restarted. On restarting the pilot plant, influent water quality (Table 46) for the first seven days was below expectations; turbidity ranged from 1.3 to 24.0 NTU and total coliform densities varied from 7 to 36 organisms per 100 ml. As anticipated, coliforms occurred in the GAC effluent and varied in densities from 1 to 8 organisms per 100 ml for these same seven days. After that interval, the total coliform occurrence in the contactor effluent was limited to day 28 when one total coliform per 100 ml was found. Coliform passage in elevated turbidities during the period of bed stabilization was probably the mechanism for their migration. Coliform colonization on the reactivated GAC was unlikely because the low density for these bacteria never increased above coliform counts per 100 ml observed in the influent water.

Heterotrophic bacterial densities in the influent to the GAC contactor were also initially high, but declined in reduced cyclic fashion to reach densities consistently below 10 per ml by day 36 to the end of the experimental run on day 63. This trend was also detected in data on heterotrophic bacterial densities obtained from the contactor effluent. The initial run with virgin GAC and the second run after the GAC was reactivated did have measurable chlorine dioxide residuals in the influent water which were completely absorbed during passage through the contactor.

Granular activated carbon contactors are generally placed in series to provide more contact time for organic removal. This configuration also provides scheduling a staggered period for individual contactor servicing

TABLE 46. MICROBIAL QUALITY OF GAC CONTACTOR EFFLUENT USING REACTIVATED HYDRODARCO 10X30*

Testing Interval Days	Water Temp. °C	Influent to GAC Contactor				GAC Contactor Effluent			
		Turbidity NTU	SPC per ml	Total Coliforms per 100 ml	ClO_2 Residual mg/L	Turbidity NTU	SPC per ml	Total Coliforms per 100 ml	ClO_2 Residual mg/L
1	23	24.0	830	36	0.3	0.8	179	8	0.0
2	22	0.8	120	10	0.0	1.1	150	8	0.0
3	23	1.3	1,040	7	0.0	1.2	6,600	4	0.0
4	22	1.8	89	12	0.0	0.6	3,900	4	0.0
7	22	1.2	86	7	-	1.3	49	2	-
8	21	1.9	74	9	-	0.7	410	1	-
9	21	1.3	140	11	-	0.4	950	4	-
10	21	0.6	330	-	0.3	0.6	870	< 1	0.0
11	21	0.4	60	-	0.6	0.5	210	< 1	0.0
14	22	0.4	33	-	0.8	0.3	570	< 1	0.0
16	21	0.4	22	< 1	0.8	0.3	410	< 1	0.0
18	20	0.3	84	-	0.2	0.2	30	< 1	0.0
21	20	0.3	105	-	0.0	0.2	190	< 1	0.0
22	19	0.2	29	-	0.3	0.2	720	< 1	0.0
23	18	0.4	35	-	0.6	0.3	50	< 1	0.0
24	18	0.3	60	-	0.4	0.2	90	< 1	0.0
25	18	0.2	73	-	0.9	0.3	100	< 1	0.0
28	17	0.3	55	-	0.3	0.2	340	1	0.0
29	17	0.3	3	-	0.5	0.3	500	< 1	0.0
30	17	0.2	9	-	0.4	0.2	35	< 1	0.0
31	18	0.2	16	-	0.2	0.3	70	< 1	0.0
32	17	0.4	184	-	0.0	0.2	70	< 1	0.0
36	17	0.2	3	-	0.2	0.3	20	< 1	0.0
37	16	0.3	2	-	-	0.2	< 1	< 1	0.0
44	17	0.5	5	1	0.0	0.2	5	< 1	0.0
63	13	0.3	3	< 1	0.2	0.4	5	< 1	0.0

*Data from Evansville Pilot Plant

(backwashing and GAC replacement). Some interesting observations were noted in data collected from a pilot plant investigation in which four pilot contactors were placed in series and fed with effluent from the sand filters of the water plant at Jefferson Parish, La.

Data reported in Table 47 for the first thirty days of operation indicated influent water had no detectable coliforms per 100 ml and heterotrophic bacterial densities were below 50 organisms per ml. As the influent water passed through the series of contactors, there was a progressive increase in low density coliform occurrences. These results suggest passage of coliforms in densities below one organism per 100 ml from the influent with no subsequent establishment of significant coliform colonization in any of the contactors. Sequential data for days beyond that in Table 47 indicated the last coliforms (1 organism per 100 ml) detected in the individual columns in series was on day 138, 118, 40, and 40, respectively.

This pattern was not characteristic of the heterotrophic bacteria which were quick to colonize within three days and release organisms that were three logs higher in densities than detected in the influent. The heterotrophic bacterial colonization did not persist even in the warm water temperatures, declining to below 200 organisms per ml by day 107 (not shown in Table 47) for all columns. Apparently, available nutrients eventually became the limiting factor.

GAC Process Placement in Water Treatment Train

Optimizing removal of organics in process water, in theory, would suggest the GAC process be placed early in the progressive treatment of polluted surface waters used as a raw water source. In fact, powdered carbon is often applied in water impoundments to control taste and odor problems but is not adequate for many other organic removals. Obviously, the GAC filtration process can not be applied to raw surface waters with significant turbidities (above 1 NTU) because silt in these waters quickly coats the carbon particles and rapidly reduces organic adsorption capacity. Thus, settling of raw water and chemical treatment with clarification, at least, preceded the GAC process. These preceding treatment processes also remove much of the turbidity associated microbial flora which includes a wide range of environmental organisms, some of which are capable of aggressive colonization on GAC particles. What impact placement of the GAC process following clarification, or after sand filtration and with modifications in type of disinfectant or point of application has on microbial quality of the effluent was studied in a variety of field experiences.

Placement of a GAC filter adsorber on-line after chemical clarification did result (Table 48) in an approximate 85 percent reduction in turbidity to NTU values ranging from 0.3 to 0.9 at Jefferson Parish, LA. The occasional wide differences in residual turbidities reflects the entrapment of coagulant particles on the GAC bed and their migration through the filter prior to backwashing. Application of chloramines to the clarified water, prior to passage through the GAC filter adsorber, did not result in a complete reduction of total coliforms below the 100 ml base line, except for the autumn 1979 period. Disinfectant concentration and contact time

TABLE 47. MICROBIAL QUALITY OF EFFLUENTS FROM CONTACTORS IN SERIES*

Testing Interval Day	Water Temp. °C	Influent Series Contactors		1st Contactor Effluent		2nd Contactor Effluent		3rd Contactor Effluent		4th Contactor Effluent	
		SPC per ml	Total coliforms per 100 ml	SPC per ml	Total coliforms per 100 ml	SPC per ml	Total coliforms per 100 ml	SPC per ml	Total coliforms per 100 ml	SPC per ml	Total coliforms per 100 ml
1	13.8	27	< 1	58	< 1	66	1	60	1	87	1
2	14.0	13	< 1	71	< 1	150	2	120	1	160	1
3	14.3	20	< 1	170	1	3,300	1	5,000	1	1,200	1
4	14.5	42	< 1	410	< 1	5,900	3	8,600	1	7,800	1
5	14.5	39	< 1	2,300	< 1	8,500	4	8,600	2	7,800	3
6	14.7	30	< 1	1,800	1	2,200	2	1,800	3	1,200	1
8	15.4	10	< 1	1,700	< 1	3,700	1	7,400	1	4,000	1
9	15.8	10	< 1	5,600	1	4,500	1	5,800	1	5,600	1
10	15.3	9	< 1	3,800	< 1	6,200	< 1	9,300	1	6,800	1
11	16.0	7	< 1	2,700	< 1	2,700	1	2,800	1	3,400	1
13	15.7	16	< 1	15,000	< 1	9,700	< 1	12,000	1	18,000	1
14	15.7	18	< 1	11,000	< 1	12,000	< 1	61,000	1	27,000	1
15	16.0	36	< 1	8,800	1	6,000	1	11,000	1	6,600	< 1
16	16.2	19	< 1	15,000	1	7,800	1	14,000	< 1	18,000	1
17	15.8	21	< 1	14,000	< 1	15,000	1	12,000	1	10,000	< 1
18	16.7	6	< 1	15,000	< 1	11,000	< 1	16,000	1	14,000	< 1
19	16.7	11	< 1	12,000	< 1	9,400	1	13,000	< 1	13,000	1
20	17.5	19	< 1	4,000	< 1	8,000	1	8,300	1	8,000	1
21	18.0	24	< 1	18,000	< 1	15,000	< 1	14,000	1	11,000	< 1
22	17.8	13	< 1	12,000	< 1	11,000	< 1	8,600	< 1	8,200	1
23	17.5	19	< 1	11,000	< 1	9,800	< 1	7,600	< 1	6,400	< 1
25	17.8	4	< 1	6,900	1	6,200	< 1	5,100	< 1	6,300	< 1
26	17.8	6	< 1	5,300	< 1	4,000	< 1	3,800	< 1	4,500	< 1
27	18.0	11	< 1	5,900	< 1	2,300	< 1	1,600	3	2,300	6
28	17.8	22	< 1	8,900	< 1	4,000	< 1	5,600	< 1	6,800	< 1
29	18.8	16	< 1	8,400	< 1	5,100	1	5,400	< 1	4,100	1
30	18.8	16	< 1	4,900	< 1	1,900	< 1	750	< 1	1,300	< 1

*Data from Jefferson Parish, La. Pilot Study: April 6–May 6, 1979.

TABLE 48. MICROBIAL QUALITY OF GAC FILTER ADSORBER EFFLUENT RECEIVING CLARIFIED PROCESS WATER*

Water Treatment Process	Year/ /Season**	Water		Turbidity NTU	SPC per ml	Total Coliform per 100 ml	Total Chlorine Residual mg/L
		Temp. °C	pH				
Clarified Processed Water (Influent to GAC filter adsorber)	1978						
	Winter	4.8	8.7	2.5	-	-	1.64
	Spring	16.1	8.5	2.0	-	-	1.62
	Summer	30.0	8.4	2.8	1,300	60.0	1.57
	Autumn	18.3	7.7	3.9	530	9.6	1.57
	1979						
	Winter	7.1	7.6	2.9	440	15.3	1.90
	Spring	20.9	7.3	2.7	120	8.3	1.45
	Summer	28.7	7.5	2.8	210	22.1	1.29
	Autumn	24.0	7.5	2.7	140	< 0.1	2.13
Filter Adsorber Effluent							
	1978						
	Winter	-	8.7	0.5	24	0.4	0.83
	Spring	-	8.4	0.3	62	2.7	0.63
	Summer	-	8.0	0.3	2,800	5.8	0.00
	Autumn	-	7.5	0.8	750	1.5	0.00
	1979						
	Winter	-	7.3	0.9	425	< 0.1	0.00
	Spring	-	7.1	0.4	2,850	6.0	0.00
	Summer	-	7.2	0.3	98	12.7	0.00
	Autumn	-	7.1	0.4	110	11.8	0.00

* Data from full scale operation, Jefferson Parish, La.

**Seasonal geometric means based on 46 samples per season.

become more critical when chloramines are applied since these agents are slower acting than free chlorine. Also, total chlorine residual data include not only the active disinfectant components but some complexes of no disinfection power. As a consequence, coliforms were often found in the GAC filter adsorber effluent except during the winter period of 1979. This period of absence more likely reflected only a brief decline in filter adsorber colonization unlike the prior winter start-up period when some breakthrough occurred during filter adsorber stabilization.

Moving the GAC adsorber treatment process to after sand filtration did result in an improvement (0.1 to 0.3 NTU) for effluent turbidity (Table 49). The most beneficial effect was the improvement in the bacteriological quality of the influent. Heterotrophic bacterial densities were below 75 organisms per ml and no total coliforms were found in any of the effluent samples. This water quality improvement was a result of sand filtration effectiveness and increased contact time with chloramines added after clarification. As a result of better quality influent water to the GAC adsorber, no coliforms were detected in the GAC effluent over a three year study period. However, little difference was observed in the cyclic rise and decline of the heterotrophic bacterial population (in filter adsorber and adsorber effluents) associated with either influents.

Prechlorination of the raw source water premixed with chemicals, flocculated, ammoniated and then clarified before passage through a filter adsorber was also investigated. Chloramine residuals in the pilot plant influent water to the GAC filter adsorber can be calculated from the difference in total and free chlorine residual (Table 50) and ranged from 1.9 to 3.7 mg/l. No total coliforms were detected and the heterotrophic bacterial densities were between 2 and 17 organisms per ml. After passage through the GAC, no coliforms were detected but the heterotrophic bacterial densities were 2 or 3 logs higher for the entire 73 days of operation. Water turbidity was reduced to approximately 8 to 23 percent of the influent values.

Parallel data (Table 51) was also obtained for influent water receiving the above treatment plus sand filtration. Again, no coliforms were detected and the heterotrophic bacteria rapidly colonized the GAC adsorber to densities similar to those found for the GAC filter adsorber. Effluent turbidity reductions for the adsorber and filter adsorber were similar. As expected, the adsorber was more effective in removing TOC over 65 days than the filter adsorber, probably being a reflection of GAC particle coating by coagulant residuals from the clarifier effluent. Note the lack of any correlation between TOC and microbial activity.

Shifting disinfectant application to only breakpoint chlorination of the clarifier effluent was also investigated. While total coliforms were not found, the influent heterotrophic bacterial population was observed to be somewhat higher (Table 52). GAC filter adsorber effluents were similar to those observed in the data reported in Table 50. With the additional chlorine, contact time and passage through the sand filter, bacterial quality of the influent process water to the GAC adsorber was excellent (Table 53).

TABLE 49. MICROBIAL QUALITY OF GAC ADSORBER EFFLUENT RECEIVING SAND FILTER PROCESS WATER*

Water Treatment Process	Year/ /Season**	Water		Turbidity NTU	SPC per ml	Total Coliform per 100 ml	Total Chlorine Residual mg/L
		Temp. °C	pH				
Sand Filter Process Water (Influent to Adsorber)	1977						
	Winter	10.0	10.0	0.4	10	< 0.1	1.60
	Spring	23.5	9.9	0.2	1.7	< 0.1	1.63
	Summer	30.5	9.9	0.2	10	< 0.1	1.57
	Autumn	13.0	8.7	0.9	34	< 0.1	1.70
	1978						
	Winter	4.8	8.6	0.4	10	< 0.1	1.67
	Spring	16.1	8.5	0.3	10	< 0.1	1.62
	Summer	30.0	8.4	0.4	17	< 0.1	1.53
	Autmun	18.3	7.7	0.9	33	< 0.1	1.83
	1979						
	Winter	7.1	7.5	1.1	73	< 0.1	1.90
	Spring	20.9	7.3	0.5	27	< 0.1	1.40
	Summer	28.7	7.5	0.3	26	< 0.1	1.27
	Autumn	24.0	7.4	0.5	23	< 0.1	2.17
Adsorber Effluent							
	1977						
	Winter	-	9.9	0.3	16	< 0.1	0.00
	Spring	-	9.6	0.2	96	< 0.1	0.00
	Summer	-	9.6	0.2	685	< 0.1	0.00
	Autumn	-	8.5	0.8	138	< 0.1	0.01
	1978						
	Winter	-	8.5	0.4	31	< 0.1	0.20
	Spring	-	8.1	0.3	40	< 0.1	0.00
	Summer	-	7.9	0.2	647	< 0.1	0.00
	Autumn	-	7.4	0.7	305	< 0.1	0.00
	1979						
	Winter	-	7.3	0.8	415	< 0.1	0.00
	Spring	-	7.1	0.4	2,500	< 0.1	0.00
	Summer	-	7.2	0.3	130	< 0.1	0.00
	Autumn	-	7.1	0.4	63	< 0.1	0.00

* Data from full scale operation, Jefferson Parish, La.
**Seasonal geometric means based on 46 samples per season.

TABLE 50. GAC FILTER ADSORBER PLACEMENT AFTER CLARIFIER, PRE-CHLORINATION OF RAW WATER WITH CONVERSION TO CHLORAMINES PRIOR TO CLARIFIER*

	Water		Clarifier Effluent to GAC Filter Adsorber						GAC Filter Adsorber Effluent**			
Testing Interval Day	Temp. °C	pH	Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml	Free Chlorine Residual mg/L	Total Chlorine Residual mg/L	Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml
1	-	-	-	-	10	< 1	-	-	-	-	9,200	< 1
2	-	-	-	-	3	< 1	-	-	-	-	5,600	< 1
17	9	7.6	0.7	2.7	2	< 1	0.0	3.2	0.1	0.4	11,000	< 1
24	10	7.7	0.8	-	9	< 1	0.2	3.5	0.1	-	31,000	< 1
38	8	7.9	0.7	4.1	5	< 1	0.1	3.4	0.1	0.5	8,000	< 1
45	8	7.6	1.3	-	17	< 1	0.1	3.8	0.2	-	4,200	< 1
54	8	7.8	1.2	-	-	-	0.1	2.9	0.1	-	-	-
58	9	7.6	1.3	6.6	2	< 1	0.1	2.4	0.3	2.0	8,200	< 1
60	9	7.5	1.4	-	-	-	0.1	2.5	0.3	-	-	-
65	8	7.4	0.8	4.2	6	< 1	0.1	2.5	-	3.2	15,000	< 1
67	8	7.8	-	-	-	-	0.1	2.0	-	-	-	< 1
73	9	8.3	-	6.7	5	< 1	0.2	3.7	-	2.1	6,900	< 1

* Thornton, Colo. Pilot Plant Study using two GAC filter adsorbers in series.
**No total chlorine residual detected in effluents; columns contained Westvaco 12X40 GAC.

TABLE 51. GAC ADSORBER PLACEMENT AFTER SAND FILTRATION OF PRECHLORINATED RAW WATER WITH CONVERSION TO CHLORAMINES PRIOR TO CLARIFIER*

Testing Interval Day	Water		Sand Filter Effluent to GAC Adsorber						GAC Adsorber Effluent**			
	Temp. °C	pH	Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml	Free Chlorine Residual mg/L	Total Chlorine Residual mg/L	Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml
1	-	-	-	-	1	< 1	-	-	-	-	4,900	< 1
2	-	-	-	-	< 1	< 1	-	-	-	-	4,900	< 1
17	9	7.6	0.2	3.0	2	< 1	0.0	3.2	0.1	0.4	23,000	< 1
24	10	7.6	0.2	-	1	< 1	0.1	3.4	0.1	-	18,000	< 1
38	8	7.9	0.2	4.0	2	< 1	0.1	3.3	0.1	0.7	5,000	< 1
45	8	7.6	0.5	-	2	< 1	0.1	3.8	0.3	-	4,900	< 1
54	8	7.6	0.3	-	-	-	0.1	2.9	0.2	-	-	-
58	10	7.7	0.3	4.2	2	< 1	2.2	4.2	0.4	1.1	14,000	< 1
60	9	7.8	0.4	-	-	-	-	-	0.3	-	-	-
65	9	7.5	0.2	3.5	2	< 1	2.4	3.5	-	1.6	28,000	< 1
67	9	7.6	-	-	-	-	-	-	-	-	-	-
73	10	8.3	-	6.7	2	< 1	3.5	6.7	-	1.9	12,000	< 1

* Thornton, Colo. Pilot Plant Study using two GAC adsorbers in series.
**No total chlorine residuals detected in effluents; columns contained Westvaco 12X40 GAC.

TABLE 52. GAC FILTER ADSORBER PLACEMENT AFTER CLARIFIER INFLUENT WAS CHLORINATED TO BREAKPOINT*

Testing Interval Day	Water		Clarifier Effluent to GAC Filter Adsorber						GAC Filter Adsorber Effluent**			
	Temp. °C	pH	Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml	Free Chlorine Residual mg/L	Total Chlorine Residual mg/L	Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml
1	-	-	-	-	5	< 1	-	-	-	-	6,400	< 1
2	-	-	-	-	2	< 1	-	-	-	-	6,200	< 1
3	13	7.5	2.8	4.1	5	< 1	3.3	4.1	0.2	0.4	90,000	< 1
8	-	-	-	-	130	< 1	-	-	-	-	19,000	< 1
9	-	-	-	-	1,210	< 1	-	-	-	-	120,000	< 1
10	11	7.5	1.0	3.8	360	< 1	3.7	3.8	0.2	0.5	17,000	< 1
57	-	-	-	-	4,100	1	-	-	-	-	-	-
58	-	-	-	-	130	< 1	-	-	-	-	-	-
59	15	8.1	1.2	5.0	260	< 1	3.3	5.0	-	-	-	-
73	17	7.4	1.1	1.7	60	< 1	0.0	1.7	0.4	1.0	120,000	< 1
81	-	-	-	-	70	< 1	-	-	-	-	39,000	< 1
82	18	7.7	1.2	1.6	90	< 1	0.2	1.6	0.5	1.0	55,000	< 1
83	-	-	-	-	17	< 1	-	-	-	-	21,000	< 1

* Thornton, Colo. Pilot Plant Study using two GAC filter adsorbers in series.

**No free chlorine residuals detected in effluents; columns contained Westvaco 12X40 GAC.

TABLE 53. GAC ADSORBER PLACEMENT AFTER SAND FILTRATION WITH BREAKPOINT APPLIED TO CLARIFIER EFFLUENT*

Testing Interval Day	Water		Sand Filter Effluent to GAC Adsorber						GAC Effluent**			
	Temp. °C	pH	Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml	Free Chlorine Residual mg/L	Total Chlorine Residual mg/L	Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml
1	-	-	-	-	< 1	< 1	-	-	-	-	1,900	< 1
2	-	-	-	-	< 1	< 1	-	-	-	-	71,000	< 1
3	13	7.2	0.4	4.1	1	< 1	2.5	2.9	0.5	0.4	100,000	< 1
8	-	-	-	-	1	< 1	-	-	-	-	17,000	< 1
9	-	-	-	-	1	< 1	-	-	-	-	320,000	< 1
10	11	7.2	0.3	3.9	< 1	< 1	2.2	2.6	0.2	0.5	15,000	< 1
57	-	-	-	-	9	< 1	-	-	-	-	-	-
58	-	-	-	-	< 1	< 1	-	-	-	-	-	-
59	16	7.8	0.4	5.0	< 1	< 1	0.9	1.5	-	-	-	-
73	17	7.3	0.6	5.3	< 1	< 1	2.7	3.2	0.4	0.8	26,000	< 1
81	-	-	-	-	2	< 1	-	-	-	-	49,000	< 1
82	18	7.7	0.6	4.9	1	< 1	2.3	2.9	0.2	0.8	50,000	< 1
83	-	-	-	-	1	< 1	-	-	-	-	10,000	< 1

* Thornton, Colo. Pilot Plant Study using two GAC adsorbers in series.

**No free chlorine residuals detected in effluents; columns contained Westvaco 12X40 GAC.

Applying chlorination to only the raw water to achieve breakpoint was studied in another mode with the filter adsorber and adsorber pilot columns. As anticipated (Table 54), there was some fluctuation in heterotrophic bacterial densities and one coliform occurrence in the clarifier effluent but sand filtration (Table 55) again produced a high quality effluent to the GAC columns. In both configurations, the end results were similar: no total coliforms were found, the heterotrophic bacterial counts rapidly colonized the GAC and then proceeded in a progressive downward cyclic pattern towards densities below 1,000 by day 133 for the adsorber effluents and day 140 for the filter adsorber. Again TOC measurements did not correlate with microbial activity found in the GAC effluents.

Impact on Distribution Water Quality

The inclusion of granular activated carbon in the treatment train has repeatedly been shown to release a variety of heterotrophic bacteria and on occasion, total coliforms. This microbial activity can be adequately controlled through disinfection of finished water prior to transmission into the distribution system. However, coliform escapes into the distribution system cannot be ruled out because of several factors that afford microbial protection from contact with disinfection. These factors include releases of carbon fines, passage of aggregates or clumps of bacteria from colonization sites in GAC filtrations, and the protective nature of turbidity.

Preliminary findings from ongoing research on bacterial survival associated with carbon fines in drinking water (30) indicate carbon fines can be detected in finished water. Furthermore, carbon fines provide some measure of protection to attached Escherichia coli and enterotoxigenic (heat stable) E. coli has been isolated from carbon particles in GAC treated drinking water. While this association of a pathogen with carbon particles in distribution water was found on only one occasion, it does illustrate a pathway and a reason to minimize the release of carbon fines into finished water. Since carbon fines contribute very little to nephelometric turbidity measurements (light scattering by carbon is minimal) other approaches should be considered to monitor for carbon fine releases in finished water. One approach would be to filter a standard volume of 0.5 or 1 liter (0.1 or 0.3 gal) through a membrane filter (31) and examine for particle occurrences. Another method suggested is to filter 1,514 liters (400 gal) of finished water through a multi-layered gauze pad (32) to search for carbon fine releases in the finished water.

The water treatment train at Manchester, N.H. offered a unique opportunity to study the impact of GAC filtration applied after sand filtration. This treatment configuration, in effect, placed the GAC process within one last barrier (disinfection) of water supply transmission to the distribution system.

For this reason a variety of microbiological indicators (heterotrophic bacteria, total coliforms, acid fast bacteria and endotoxin) were included in an 18 month study of several sampling sites on the distribution system.(28,33) In addition a variety of chemical and physical tests were

TABLE 54. GAC FILTER ADSORBER PLACEMENT AFTER CLARIFIER AND BREAKPOINT CHLORINATION OF RAW WATER*

Testing Interval Day	Water		Clarifier Effluent to GAC Filter Adsorber						GAC Filter Adsorber Effluent**			
	Temp. °C	pH	Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml	Free Chlorine Residual mg/L	Total Chlorine Residual mg/L	Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml
1	18	6.9	3.7	4.3	9	< 1	1.5	1.8	0.1	0.2	4,600	< 1
21	11	8.0	1.0	4.7	6	< 1	0.4	1.0	-	0.5	150,000	< 1
28	23	7.5	0.8	3.8	9	< 1	1.4	1.7	0.1	0.6	98,000	< 1
35	22	9.4	2.0	3.2	3	< 1	1.3	1.8	0.1	0.4	12,000	< 1
42	24	7.9	0.9	4.6	39	< 1	0.3	1.0	-	0.8	31,000	< 1
49	24	8.3	1.4	4.6	190	2	1.3	1.8	0.1	1.1	47,000	< 1
56	24	8.2	1.7	4.8	7	< 1	0.4	1.0	0.1	1.4	13,000	< 1
63	22	7.5	1.0	3.9	45	< 1	0.1	0.8	0.1	1.2	14,000	< 1
71	22	7.6	1.0	3.5	24	< 1	0.7	1.1	0.1	1.7	49,000	< 1
98	19	8.3	0.7	4.1	7	< 1	2.5	2.8	0.1	0.9	950	< 1
105	19	7.6	0.5	2.5	240	< 1	1.1	1.2	0.1	1.0	14,000	< 1
112	18	7.7	0.6	3.1	2	< 1	1.4	1.8	0.1	1.4	3,300	< 1
119	17	7.5	0.6	-	52	< 1	0.6	0.8	0.1	-	18,000	< 1
126	17	7.6	0.7	3.0	1	< 1	1.2	1.6	0.2	1.0	860	< 1
133	15	7.4	0.8	-	< 1	< 1	2.7	3.0	0.2	-	3,300	< 1
140	14	7.6	-	3.0	13	< 1	0.5	0.8	-	2.0	780	< 1
147	13	7.6	-	-	36	< 1	3.5	4.0	-	-	810	< 1
154	13	7.5	-	3.0	36	< 1	2.0	2.3	-	1.4	960	< 1
161	12	7.4	-	-	12	< 1	1.7	2.1	-	-	1,100	< 1
168	8	7.5	-	2.0	5	< 1	1.7	1.9	-	1.4	830	< 1

* Thornton, Colo. Pilot Plant Study using two GAC filter absorbers in series.

**No free chlorine residual detected in effluent samples; columns contained Westvaco 12X40 GAC.

TABLE 55. GAC ADSORBER PLACEMENT AFTER SAND FILTER AND BREAKPOINT CHLORINATION OF RAW WATER*

Testing Interval Day	Water Temp. °C	Water pH	Sand Filter Effluent to GAC Adsorber Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml	Free Chlorine Residual mg/L	Total Chlorine Residual mg/L	GAC Filter Adsorber Effluent** Turbidity NTU	TOC mg/L	SPC /ml	Total Coliform /100 ml
1	18	6.9	1.1	3.5	1	< 1	2.4	2.9	0.1	0.2	9,000	< 1
21	21	7.8	0.2	4.8	< 1	< 1	2.4	2.9	-	0.5	27,000	< 1
28	23	7.3	0.1	3.3	2	< 1	2.0	2.3	0.1	0.4	6,100	< 1
35	23	7.5	0.2	3.2	1	< 1	2.0	2.4	0.1	0.4	20,000	< 1
42	24	7.7	0.2	4.6	1	< 1	2.0	2.6	-	0.6	57,000	< 1
49	23	7.3	0.1	3.8	3	< 1	2.0	2.8	0.2	0.6	7,000	< 1
56	24	7.5	0.2	4.8	< 1	< 1	2.0	2.5	0.1	1.1	6,100	< 1
63	23	7.4	0.1	4.2	1	< 1	1.6	2.0	0.1	1.0	3,600	< 1
71	23	7.9	0.1	3.3	1	< 1	1.8	2.2	0.1	1.3	18,000	< 1
98	20	8.0	0.1	3.0	1	< 1	1.8	2.1	0.1	1.2	1,500	< 1
105	20	7.4	0.1	2.7	1	< 1	0.9	1.3	0.1	2.0	1,200	< 1
112	18	7.7	0.1	3.2	1	< 1	1.0	1.3	0.1	1.2	580	< 1
119	18	7.5	0.1	-	1	< 1	1.9	2.2	0.1	-	21,000	< 1
126	18	7.7	0.1	3.0	1	< 1	2.9	3.2	0.1	1.0	580	< 1
133	16	7.4	0.2	-	1	< 1	2.0	2.5	0.1	-	640	< 1
140	14	7.6	-	4.0	2	< 1	1.7	2.0	-	1.0	240	< 1
147	14	7.8	-	-	2	< 1	2.5	2.9	-	-	240	< 1
154	13	7.5	-	3.8	1	< 1	1.8	2.0	-	1.2	190	< 1
161	12	7.4	-	-	1	< 1	1.6	2.0	-	-	870	< 1
168	8	7.4	-	1.7	1	< 1	1.2	1.5	-	0.7	85	< 1

* Thornton, Colo. Pilot Plant Study using two GAC adsorbers in series.

**No free chlorine residual in effluent samples; columns contained Westvaco 12X40 GAC.

done on each sample to characterize the water. Water examinations were made of the combined effluent from several GAC adsorbers finished water and three sampling stations on the distribution system (Table 56).

Acid fast bacteria, proposed as a more restrictive indicator of disinfection effectiveness,(34) were found to decline through the treatment train and in distribution were only recovered in densities that averaged one or two organisms per liter. This result suggests that these organisms never successfully colonized either the treatment processes or the distribution system and offered no particular advantage over coliforms in measuring disinfection effectiveness.

As noted in other field studies,(29,33) total organic carbon did not appear to be important in governing microbial densities found in treatment processes or in distribution water. What appears lacking is specificity to biodegradable organics rather than total available organics that include numerous long chain compounds not readily metabolized by microorganisms that colonize carbon filters. Likewise, the total endotoxin measurements were found to have no correlation with the microbial indicators selected.(35) Total endotoxin relates to total biological activity of which the indicators selected are only a small percent of all biological forms present in the effluents or on the packed material in the GAC filter bed.

Total coliforms were found on several occasions in finished water and distribution samples, during warm water periods (Table 57). It is interesting to note that coliforms found in the post combined carbon filter effluents were generally inactivated by the final disinfection process but there were two instances documented where coliforms passed into the finished water. The inconsistency of detecting coliforms in the finished water at all periods when those organisms were found in the distribution system is more a weakness of the sampling frequency of the system than a colonization event observed in very low density coliform occurrences. The data also illustrates the value of using a one liter sample size to examine finished water.

Another important finding was that full scale GAC treatment resulted in a statistically significant increase in heterotrophic bacterial densities as compared to a similar plant (Concord, N.H.) that does not employ GAC.(28) Furthermore water temperature, pH and turbidity had a positive influence on heterotrophic bacterial densities.(33) These physical-chemical conditions of water are key factors that also impact disinfection effectiveness.

Summary

Granular activated carbon filters and GAC contactors used in water supply treatment have been investigated in a variety of treatment train configurations used in pilot plant systems and in full scale treatment operations. Microbial activity does occur in GAC processes with regrowth related to biodegradable organics and warm water periods. Bacterial populations in GAC filter beds can be minimized through application of disinfection to the influent waters. All carbon materials used for organic removal can become colonization sites for some bacteria in water passing

TABLE 56. BACTERIAL, PHYSICAL AND CHEMICAL QUALITY CHARACTERISTICS IN WATER TREATMENT INVOLVING GAC FILTRATION*

Sampling Site	1980 Date	Water		Turbidity NTU	TOC mg/L	Free Chlorine Residual mg/L	Total Endotoxin mg/L	SPC /ml	Acid Fast Bact/L	Total Coliform /100 ml**
		Temp. °C	pH							
Pre-Flash Mix	April 15	9.5	6.6	1.5	6.96	0.0	-	29	6	24
	April 30	11.5	6.4	4.2	7.25	0.0	-	25	2	2
	May 13	14.8	6.5	5.7	6.75	0.0	-	40	4	2
	June 3	20.5	6.8	0.4	7.04	0.0	-	66	3	4
	June 17	20.5	6.6	0.5	6.32	0.0	-	340	5	10
	July 1	22.5	6.5	0.5	5.00	0.0	-	600	2	< 1
	July 15	23.8	6.5	0.7	5.40	0.0	-	1,063	< 1	33
	July 29	27.0	6.5	0.8	5.40	0.0	-	168	0.4	< 1
	Aug. 26	23.3	6.5	1.1	6.59	0.0	-	2,640	< 1	< 0.01
	Sept. 3	-	6.4	0.8	-	0.0	-	200	-	8
	Sept. 9	22.5	6.4	0.5	8.67	0.0	-	540	1.2	< 0.01
	Sept. 30	17.0	6.2	1.0	5.94	0.0	4.9	171	0.07	1
	Oct. 14	13.8	6.3	0.8	6.16	0.0	12.6	390	0.13	2
	Oct. 28	9.7	6.3	0.6	6.29	0.0	2.5	190	1.6	10
	Nov. 11	7.0	6.5	1.5	8.76	0.0	11.0	232	1.3	6
	Dec. 2	4.0	6.8	0.8	5.30	0.0	13.3	80	1.7	15
Sand Filtered Effluent	April 15	10.0	6.0	0.4	4.92	0.0	-	29	6	< 0.01
	April 30	12.0	5.8	0.4	3.76	0.0	-	1	1	< 0.01
	May 13	14.3	6.1	0.4	4.24	0.0	-	8	0.1	< 0.01
	June 3	20.5	6.4	0.3	6.40	0.0	-	4	0.1	< 0.01
	June 17	20.5	6.1	0.4	5.64	0.0	-	85	0.13	< 0.01
	July 1	22.5	5.9	0.5	4.16	0.0	-	127	0.2	0.03
	July 15	24.0	5.9	0.6	3.28	0.0	-	1	0.05	< 0.01
	July 29	27.5	6.0	0.3	4.56	0.2	-	0.3	0.07	< 0.01
	Aug. 26	23.5	6.0	0.5	5.05	0.0	-	4.0	1	< 0.01
	Sept. 3	-	7.0	0.2	-	0.0	-	< 0.1	-	1
	Sept. 9	23.0	6.1	0.7	6.67	0.0	-	1	0.17	< 0.01
	Sept. 30	17.5	6.0	0.6	5.61	0.2	2.75	< 0.1	< 0.01	0.04
	Oct. 14	14.5	5.9	0.3	5.72	0.0	0.00	1	0.04	< 0.01
	Oct. 28	10.3	6.2	0.5	3.93	0.0	3.90	2	< 0.01	< 0.01
	Nov. 11	7.6	6.3	0.6	6.40	0.4	0.00	-	0.07	< 0.01
	Dec. 2	4.0	5.7	0.8	3.70	0.0	1.90	1	0.04	< 0.01
Post Combined Carbon Effluent	April 15	9.0	5.8	0.2	12.12	0.0	-	6	-	0.03
	April 30	11.5	5.5	0.2	2.72	0.0	-	1	0.13	0.10
	May 13	14.5	5.8	0.4	3.36	0.0	-	5	0.20	-
	June 3	20.1	6.0	0.4	6.80	0.0	-	12	0.13	< 0.01
	June 17	19.5	5.9	0.2	3.68	0.0	-	88	0.13	< 0.01
	July 1	22.8	6.0	0.4	2.96	0.0	-	557	< 0.01	< 0.01
	July 15	24.0	6.2	0.4	4.32	0.0	-	23	0.35	< 0.01
	July 29	28.0	5.9	0.7	3.40	0.0	-	155	0.30	< 0.01
	Aug. 26	23.5	5.9	0.5	4.91	0.0	-	109	0.17	< 0.01
	Sept. 3	25.4	7.0	0.2	-	0.0	-	-	-	1
	Sept. 9	23.0	6.0	0.4	4.88	0.0	-	6,330	< 0.01	< 0.01
	Sept. 30	17.0	5.8	0.8	4.22	0.0	4.86	76	< 0.01	< 0.01
	Oct. 14	14.0	5.9	0.5	4.65	0.0	5.75	14	0.07	< 0.01
	Oct. 28	10.0	6.2	0.7	4.29	0.0	0.00	38	0.27	< 0.01
	Nov. 11	7.6	5.5	0.3	4.86	0.0	2.25	9	< 0.01	< 0.01
	Dec. 2	4.0	6.0	0.8	3.60	0.0	2.75	0.3	0.07	< 0.01

* Data from Manchester, N.H. full scale operations.
**Data calculated from triplicate one liter samples.

TABLE 57. BACTERIAL, PHYSICAL AND CHEMICAL QUALITY CHARACTERISTICS IN DISTRIBUTION WATER TREATMENT INVOLVING GAC FILTRATION*

Sampling Site	1980 Date	Water Temp. °C	pH	Turbidity NTU	TOC mg/L	Free Chlorine Residual mg/L	Total Endotoxin mg/L	SPC /ml	Acid Fast Bact/L	Total Coliform /100 ml**
Finished Water	Apr. 15	9.8	6.9	0.4	4.12	0.9	–	2	0.2	0.03
	Apr. 30	11.5	7.0	0.6	3.00	1.2	–	1	< 0.01	< 0.01
	May 13	14.0	7.0	0.3	5.68	1.3	–	2	0.07	< 0.01
	June 3	20.3	7.7	0.3	6.28	0.8	–	5	0.30	0.03
	June 17	19.5	7.1	0.1	5.80	0.7	–	1	0.30	< 0.01
	July 1	22.5	6.8	0.3	2.62	1.5	–	3	0.03	< 0.01
	July 15	23.8	7.3	0.3	3.10	1.4	–	1	0.20	< 0.01
	July 29	28.0	6.7	0.4	3.24	1.3	–	< 0.1	0.30	< 0.01
	Aug. 26	23.5	7.1	0.5	5.27	1.3	–	9	0.43	< 0.01
	Sept. 9	22.8	7.4	0.4	6.67	2.1	–	1	0.03	< 0.01
	Sept. 30	17.8	6.9	0.8	3.61	1.5	6.55	0.3	0.10	< 0.01
	Oct. 14	14.5	6.8	0.9	3.12	0.9	0.00	57	0.13	< 0.01
	Oct. 28	10.0	7.5	0.6	3.48	0.9	0.00	1	0.07	< 0.01
	Nov. 11	7.5	7.3	0.3	4.70	0.9	0.00	2	0.13	< 0.01
	Dec. 2	3.8	6.8	1.0	2.80	0.9	2.80	< 0.1	0.17	< 0.01
Distribution (7 L)	Apr. 15	9.9	5.1	0.6	4.16	0.4	–	1	–	< 0.01
	Apr. 30	11.5	5.1	1.5	4.32	0.5	–	1	0.03	< 0.01
	May 13	13.5	6.1	0.6	3.40	0.4	–	0.7	0.20	< 0.01
	June 3	18.5	6.7	0.2	4.60	0.5	–	2	0.33	0.03
	June 17	22.1	7.1	0.2	3.28	0.2	–	23	0.17	< 0.01
	July 1	21.5	6.9	0.5	2.96	0.5	–	1	0.03	< 0.01
	July 15	22.8	–	0.4	2.12	0.7	–	1	0.10	< 0.01
	July 29	26.0	6.3	0.5	3.84	0.5	–	1	0.17	< 0.01
	Aug. 26	23.5	7.2	0.5	6.00	0.5	–	2	0.10	< 0.01
	Sept. 3	–	6.4	0.3	–	–	–	2	–	< 0.01
	Sept. 9	24.0	6.6	0.6	4.59	0.6	–	< 0.1	0.03	< 0.01
	Sept. 30	20.0	6.7	0.6	3.90	0.7	3.40	2	0.03	< 0.01
	Oct. 14	16.5	6.7	0.5	3.44	0.7	5.50	2	0.13	< 0.01
	Oct. 28	14.5	6.3	0.4	3.48	0.2	0.00	1	0.17	< 0.01
	Nov. 11	–	–	–	–	–	–	–	–	–
	Dec. 2	7.8	7.2	0.8	3.20	0.5	20.00	< 0.1	0.27	< 0.01
Distribution (15 L)	Apr. 15	8.8	5.4	1.0	4.32	0.3	–	4	–	< 0.01
	Apr. 30	11.0	4.8	0.8	2.92	0.2	–	0.3	< 0.01	0.03
	May 13	12.5	5.9	0.3	8.80	0.2	–	1	0.10	0.03
	June 3	17.2	6.6	0.2	3.90	0.2	–	1	6.00	< 0.01
	June 17	17.8	6.9	0.2	3.08	0.2	–	7	0.10	< 0.01
	July 1	20.5	6.9	0.5	2.36	0.5	–	< 0.1	0.10	< 0.01
	July 15	21.5	–	0.4	2.32	0.5	–	1	0.05	< 0.01
	July 29	24.0	6.3	0.2	2.32	0.4	–	3	0.07	< 0.01
	Aug. 26	23.0	6.8	0.4	4.51	0.0	–	1	< 0.01	< 0.01
	Sept. 9	23.3	6.2	0.3	6.00	0.2	–	2	0.30	68
	Sept. 30	21.5	6.4	0.5	3.99	0.5	9.00	1	0.03	0.01
	Oct. 14	18.0	6.6	0.4	3.32	0.4	7.90	0.3	0.05	0.03
	Oct. 28	15.8	6.0	1.3	3.01	0.2	0.00	6	0.07	< 0.01
	Nov. 11	12.8	6.6	0.2	3.86	0.5	2.35	3	< 0.01	< 0.01
	Dec. 2	9.8	6.5	0.6	3.30	0.3	3.40	< 0.1	0.07	< 0.01

* Data from Manchester, N.H. full scale operations.

**Data calculated from triplicate one liter samples.

through the filter bed. This material may also become contaminated from bulk storage in unprotected areas, placement in converted sand filter beds not adequately cleaned or from transfer of GAC in contaminated slurry to filter beds. Reactivation of GAC may cause some particle size reduction and change in surface characteristics that appear to have little effect on the ability of heterotrophic bacteria to find sites for attachment and colonization. Carbon fines in GAC material may be a transport vehicle for bacteria during the stabilization period of a new bed with virgin GAC or filter replaced with reactivated GAC.

The higher velocity of process water passing through pressure contactors or adsorbers does minimize the continued presence of high densities for heterotrophic bacteria in the GAC effluent after a stabilization of these systems is realized. Total coliform regrowth also appears to be minimized in these closed devices. Filter adsorbers are impacted by floc or silt that coats the carbon particles. This condition contributes to shorter usefulness of the adsorption process and to the potential for colonization by coliforms with their subsequent release into the GAC process effluent. Connecting contactors in series in one pilot study indicates coliform passage from one contactor to another can occur with releases in the final effluent. However, colonization was not permanently established in any of the four contactors in series.

Careful consideration must be given to placement of the GAC process in the water treatment train as it relates to optimizing organic removal, GAC bed life, and controlling microbial resurgence by effective disinfection. Stabilization of the GAC bed after backwashing should be achieved quickly to avoid significant passage of floc, silt, carbon fines and bacterial aggregates through the final stages of treatment. Using chlorinated backwash water, more frequent backwashing and discharging the start-up GAC filter effluent to waste for the first 10 minutes is desirable. Application of disinfection to GAC filter influents and prior sand filtration will optimize the production of effluents which will not contain coliform bacteria in 100 ml test portions.

The effects that GAC treatment has on distribution water quality is largely unknown from field operations. In theory, the long term benefit to improve microbial quality of water in distribution would be a reduction in available nutrients (organics) to support bacterial regrowth in the pipe sediments and tubercles, provided GAC is replaced or reactivated frequently. Since GAC treatment does result in significant bacterial activity farther into the treatment train, more attention should be given to monitoring finished water for the appearance of carbon fines and coliform occurrences in liter volume test samples.

A pathway involving passage of carbon particles, coliform attachment and protection from disinfection inactivation has not been clearly demonstrated in published case history reports on coliform problems in distribution networks. However, it should be noted that some of the water systems involved used carbon capped filters or GAC filtration. Investigation of bacterial quality in a water system using GAC treatment did reveal evidence of a protected pathway for coliform passage from carbon effluent through final disinfection then out into the distribution system on one occasion. These coliform occurrences were based on three replicate examinations of one liter samples and illustrate how very low densities of coliforms go undetected when only 100 ml sample volumes are analyzed.

An extensive review of bacteriological data from a variety of pilot plant and full scale operations, using GAC treatment was made for this report. Major items included GAC characteristics, sanitary quality of virgin carbon, GAC reactivation effects, gravity filtration vs. pressure contactors, significance of GAC placement in the water treatment train and the potential impact on microbial quality of distribution water. None of these issues are beyond control using reasonable treatment precautions by water plant operators. However, there is a need to revise the monitoring of finished water for detection of carbon particle releases and coliform densities at one liter levels so as to provide more useful information to fine tune treatment effectiveness.

SECTION IX

GAC TREATMENT COST EXPERIENCE

Detailed construction and operational costs were collected at the Cincinnati Water Works (CWW) and the Manchester Water Works (MWW). This actual cost experience has been supplemented with cost estimates for various GAC treatment scenarios in order to examine the effect of economies of scale and the cost tradeoffs among alternative GAC treatment systems. These cost estimates are based on the information obtained for various GAC projects including the CWW and MWW research projects and the use of preliminary cost estimating functions developed by the Drinking Water Research Division (DWRD) of EPA (2,4,36-38). The cost estimating equations and assumptions used in performing this analysis are presented in the Appendix. This provides an analytical tool for one to generate their own updated cost estimates of various GAC system scenarios using specific design and cost parameters applicable to a particular case.

Costs Associated with the Cincinnati Water Works GAC Systems

The pertinent background cost data used in the CWW cost calculations are shown in Table 58. The upper section of the table displays the cost rates charged to various resources used in operating the GAC systems. The middle section of the table presents the water throughput for the filter adsorbers and contactors and the amount of GAC required to be reactivated as applicable to the cost analysis. The bottom section of the table shows the amortization periods for various equipment and facilities used in calculating the annual capital costs. The detailed capital costs incurred in the project for equipment and facilities are given in Table 59. Table 60 presents the representative operation and maintenance (O&M) and amortized capital costs (1979-1980) associated with the two modes of GAC adsorption and on-site reactivation.

Table 60 presents "actual" and "optimum" costs for the filter adsorbers, contactors, and reactivation. "Actual" annual cost values were based on unit costs determined by averaging actual expenses incurred during a time frame most representative of typical operation in this research project. These costs reflect the fact that the GAC from the filter adsorbers and contactors was not reactivated exactly according to plan. The ideal plan was to reactivate carbon from filter adsorbers on a six week cycle and reactivate carbon from contactors on a three month cycle. The "optimum" O&M cost values refer to the estimated costs that would have been experienced if the ideal operating and reactivation plan had been rigidly practiced. The "optimum" capital cost values refer to the annual capital costs determined using an amortization period of 20 years instead of the useful life periods shown in Table 58.

TABLE 58. CINCINNATI WATER WORKS COST AND SYSTEM PARAMETERS

	Metric	English
Power	2.19 - 2.91 ¢/kWh	2.19 - 2.91 ¢/kWh
Natural Gas	11.1 - 11.9 ¢/m^3	31.0 - 33.8 ¢/ccf
Water	11.1 ¢/m^3	42.2 ¢/1,000 gal
GAC	1.08 - 1.17 $/kg	49 - 53 ¢/lb
Labor		
Contactor & Furnace	8 $/hr	8 $/hr
General Labor	6.50 $/hr	6.50 $/hr
Maintenance	7 - 9 $/hr	7 - 9 $/hr
Natural Gas Fuel Value	35,300 BTU/m^3	1,000 BTU/ft^3
Reactivation Fuel Use	13,200 BTU/kg GAC	6,000 BTU/lb GAC

	Actual	Optimum	Actual	Optimum
GAC Systems Throughput				
GAC Filters	9,008 mil L/yr	11,165	2,380 mg/yr	2,950
Contactors	4,542 mil L/yr	5,300	1,200 mg/yr	1,400
Total	13,550 mil L/yr	16,465	3,580 mg/yr	4,350
Reactivation Requirements				
GAC Filters	464,442 kg/yr	665,402	1,023,000 lbs/yr	1,465,644
Contactors	342,134 kg/yr	270,328	753,600 lbs/yr	595,437
Total	806,576 kg/yr	935,730	1,776,600 lbs/yr	2,061,081

GAC Filters

Initial GAC Inventory - 20 year life

Contactors

Initial GAC Inventory - 20 year life
Contactors and Instrumentation - 8 year life
Building - 25 year life

Reactivator

Furnace, Tanks & Controls - 15 years
Building - 25 years

All capital costs are amortized at 10% over the useful life span indicated.

TABLE 59. CINCINNATI WATER WORKS DETAILED CAPITAL COSTS

Building	
Foundation & Tunnel	$ 70,700
Building heat., Vent. & Light	175,190
Floor & Drain System	52,100
Potable Water Piping	3,080
Final Connections	8,160
Misc.	4,210
Engineering, Design	44,520
Engineering, Resident	20,970
Total Building	378,940
Contactors	
Pressure Vessels (4)	355,550
Sample Troughs	24,310
Influent/Effluent Piping	156,380
Process Pumps	37,370
Backwash Piping	77,490
GAC Transport Piping	60,100
Compressed Air Equip.	38,130
Switchgear	53,500
Painting	12,100
Engineering, Design	82,920
Engineering, Resident	16,540
GAC Installation Labor	920
Initial GAC	85,290
Total Contactors	$1,000,600
GAC Filters (2)	
Sand Removal Labor	2,000
GAC Installation Labor	1,400
Sample Units	11,190
Turbidimeters	2,030
Initial GAC	96,250
Total GAC Filters	$ 112,870
Reactivator	
Furnace	248,230
Instrumentation	224,500
Storage Tanks (2)	53,650
Steam Generator and Piping	14,900
Sand Separator	13,850
Motor Control Center & wiring	17,010
Water Piping	9,810
Drain Piping	7,220
GAC Transport Piping	38,900
Engineering, Design	84,780
Engineering, Resident	7,410
Final Connections	38,630
Total Reactivator	$ 758,890
TOTAL CAPITAL COST	$2,251,300

TABLE 60. CWW 1979-1980 REPRESENTATIVE ANNUAL O&M AND CAPITAL COSTS ($/YEAR)

	GAC Filters 0.44 m^3/s (10 mgd)		Contactors 0.17 m^3/s (4 mgd)		Reactivation 227 kg/hr (500 lb/hr)	
	Actual	Optimum	Actual	Optimum	Actual	Optimum
GAC transport water	$1,380	1,930	980	930	-	-
Process water	-	-	-	-	14,800	17,000
Pumping electric	-	-	12,670	14,790	-	-
Building electric	-	-	3,810	3,810	3,810	3,810
Furnace electric	-	-	-	-	4,440	5,100
Natural gas	-	-	-	-	35,520	40,900
Transport labor & GAC process	57,400	80,360	40,960	39,380	-	-
Furnace labor	-	-	-	-	12,500	12,500
Maintenance labor	-	-	-	-	66,850	66,850
Maintenance material	-	-	-	-	1,540	1,540
GAC makeup, filters	-	-	-	-	97,400	136,360
GAC makeup contactor	-	-	-	-	53,920	51,220
Amortized capital	13,260	13,260	202,460	139,790	120,650	111,390
	72,040	95,550	260,880	198,700	411,430	446,670
Allocated reactivation cost	247,176	320,600	164,254	126,070		
Total ($/year)	319,216	416,150	425,134	324,770		

- (non-applicable)

Very little capital costs or electrical operating costs were included for the GAC filter adsorber system because no additional costs were incurred above that which was normally required for sand filters. The costs presented in this analysis reflect only the additional costs required by the use of each type of GAC system.

The most significant O&M costs in both types of GAC systems were the total labor expense, the cost of makeup GAC, and the cost of fuel. The GAC filter adsorber system experienced an average GAC loss of 18.5% by volume (bed-to-bed) as a result of reactivation and handling. The contactor system experienced an average carbon loss of 15% by volume (contactor-to-contactor). Carbon transport for the filter adsorbers was performed manually and probably contributed to the higher GAC losses experienced through excessive handling.

The backwash criterion of 138K Pa (20 psig) head loss was never exceeded in the contactors during the study period. Therefore, the contactor system pumping electric costs primarily consisted of influent pumping. The contactor system capital and fluid-bed reactivation capital represented very significant costs to the systems. The large difference in cost between the "actual" capital cost value and the "optimum" capital cost value for the contactor system is a result of the "actual" value being based on a useful life of 8 years and the "optimum" value being based on a useful life of 20 years (making the annual cost much less for the 20 year useful life).

A summary of the unit costs for the two adsorption systems and on-site reactivation is presented in Table 61. In comparing the unit costs for GAC filter adsorbers and contactors, the most significant difference is found in the capital costs. In the research project, no structural changes were made to the conversion filter beds, only some inexpensive features were added. Therefore, the GAC filter adsorber system exhibited very little capital costs. However, the contactors required completely new construction resulting in significant capital costs.

TABLE 61. CINCINNATI WATER WORKS UNIT COST SUMMARY

	[¢/1000 gal water throughput][a]				[¢/lb GAC input][b]	
	GAC filters 0.44 m^3/s (10 mgd)		Contactor 0.17 m^3/s (4 mgd)		Reactivation 230 kg/hr (500 lb/hr)	
	Actual	Optimum	Actual	Optimum	Actual	Optimum
O&M	2.47	2.79	4.87	4.21	16.37	16.27
Capital	.56	.45	16.87	9.91	6.79	5.40
Subtotal	3.03	3.24	21.74	14.20	23.16	21.67
Allocated Reactivation	10.38	10.86	13.68	9.00		
Total	13.41	14.10	35.42	23.20		

[a]To determine ¢/m^3 multiply by 0.2642.
[b]To determine ¢/kg divide by 0.454.

The capital cost of on-site fluid bed reactivation represented about 29% of the total reactivation system cost and about 71% of the O&M costs. The total unit cost for the 5,448 Kg (12,000 lbs) fluid bed reactivation system was 51.0 ¢/kg (23.16 ¢/lb) of GAC required to be reactivated. For CWW, the unit cost for purchased virgin replacement GAC was about 110 ¢/kg (50 ¢/lb). In comparison, on-site fluid bed reactivation was very cost-effective in relationship to replacement of spent carbon with purchased virgin GAC.

Prorating the GAC reactivation cost between the two types of adsorption systems results in a total unit cost of 3.54 ¢/m^3 (13.41 ¢/1000 gal) for the filter adsorber system and 9.35 ¢/m^3 (35.42 ¢/1000 gal) for the contactor system. Again, the large difference in cost is primarily attributed to the large additional capital costs associated with the GAC contactor facility versus negligible additional capital costs associated with the GAC filter adsorbers. These total unit costs should not be considered indicative of the costs for a complete plant conversion to GAC treatment, and one should not conclude that a sand-replacement filter adsorber system is more cost-effective than the contactor system.

The contactor facilities were built primarily for research purposes adding significantly to their cost. Also, the short useful life of 8 years used in determining the amortized capital resulted in high annual cost values. In a complete plant application of a GAC contactor system the unit amortized capital cost is expected to be significantly less than that incurred in the research project. Application of GAC filter adsorbers in a complete plant conversion would require the addition of filters and GAC storage to compensate for the reduction in plant capacity as a result of frequent filter changeovers for reactivation. Therefore, the unit capital cost for a GAC filter adsorber system is expected to increase significantly in a complete full-scale operation.

Maintenance costs were practically non-existent during the research project because most of the equipment and facilities were new and covered under warranties. This is not representative of continued real-life operation and must be included in a cost estimate for complete plant conversion. During the project, manual labor was required for carbon transport which resulted in higher labor costs and probably higher GAC losses from excessive handling (thus increasing GAC makeup costs). In a large-scale GAC operation it is expected that these costs could be reduced using a more automated carbon transport system.

Even in terms of relative costs, the total unit cost values for the GAC filter adsorber system and contactor system shown in Table 61 should not be used in evaluating the cost tradeoffs between the two types of systems. The two types of adsorption systems are not presented on an equal basis. The GAC filter adsorber system is presented as a 37,850 m^3/d (10 mgd) facility with an EBCT of 7.5 minutes while the GAC contactor system is presented as a 15,140 m^3/d (4 mgd) facility with an EBCT of 15.3 minutes. One would expect lower unit costs with a system of larger scale and less stringent treatment criteria. In order to make a more valid cost comparison between a sand replacement GAC filter adsorber system and a GAC contactor adsorption system, an equal basis must be established (i.e., common plant capacity and operation, and common treatment criteria). The following discussion presents a cost evaluation of the two types of GAC adsorption systems, compared using common criteria, as applicable to a complete plant conversion to GAC treatment at the CWW.

Cost Estimates for Complete Plant Conversion to GAC at the Cincinnati Water Works

In order to examine the costs associated with a complete plant conversion to GAC treatment evaluating alternative systems, cost estimates for both sand-replacement GAC filter adsorber systems and steel pressure GAC contactor systems have been generated. Table 62 presents cost estimates for four complete GAC systems (adsorption with on-site fluid bed reactivation) at the CWW.

The cost estimates are given in 1984-dollars and calculated using information derived from the research project and cost data obtained from a previous USEPA study.(36) The systems examined were based on a plant capacity of 889,475 m^3/d (235 mgd) and an average water production of 529,900 m^3/d (140 mgd). Two alternative sand-replacement GAC filter adsorber systems are presented each having an EBCT of 7.5 minutes, one with a treatment criteria of 1.5 mg/L TOC and the other with 1.0 mg/L TOC. Two alternative steel pressure GAC contactor systems are presented for a treatment criteria of 1.0 mg/L TOC, one using an EBCT of 15.2 minutes and the other an EBCT of 20 minutes. The cost tradeoffs between the GAC filter adsorber alternative with a treatment criteria of 1.0 mg/L TOC and the two GAC contactor alternatives (both with the 1.0 mg/L TOC criteria) can be evaluated because all three alternative systems are compared on a common basis of treatment criteria.

In examining the capital costs for the four systems, the GAC contactors realize slightly higher costs as one would expect with increasing depth and volume of GAC (increasing EBCT). In examining the O&M costs, the contactor system with the longest EBCT (20 minutes) incurs the lowest O&M cost as it has the longest GAC service life (given the 1.0 mg/L TOC goal) and requires less frequent carbon reactivation. The other contactor system alternative (EBCT = 15.2 minutes) has an O&M cost of about one-half of the O&M cost of the GAC filter adsorber system (EBCT = 7.5 minutes) given the same treatment goal (1.0 mg/L TOC). The shorter EBCT in the filter adsorber system produces a much shorter GAC service life and thus results in more frequent reactivations. The GAC filter adsorber system alternative with the 1.5 mg/L TOC goal incurs a significantly lower O&M cost than the same system with the 1.0 mg/L TOC goal because the relaxed treatment goal increases GAC service life and results in less frequent reactivations.

Given the 1.0 mg/L TOC treatment goal, the GAC contactor system with the EBCT of 20 minutes exhibits the lowest total unit cost at 4.17 ¢/m^3 (15.8 ¢/1,000 gal). Even though this alternative incurs the highest capital cost, the GAC service life is long enough to provide significantly lower O&M costs

TABLE 62. COST ESTIMATES (1984 DOLLARS) FOR CINCINNATI COMPLETE PLANT CONVERSION TO GAC TREATMENT

	GAC Filters		GAC Contactors	
	Treatment Goal		Treatment Goal	
	1.5 mg/L TOC	1.0 mg/L TOC	1.0 mg/L TOC	1.0 mg/L TOC
EBCT (minutes)	7.5	7.5	15.2	20.0
Critical Summer Service Life (days)	31	14	66	114
Captial Cost (\$/year)[a]	3,607,411	5,116,213	5,280,807	5,884,324
O&M Cost (\$/year)[b]	4,039,311	8,672,638	4,341,719	3,304,890
Total Cost (\$/year)	7,646,722	13,788,851	9,622,526	9,189,214
Unit Cost (¢/1000 gal)[c]	14.9	26.9	18.8	17.9

[a] Amortized at 10% for 20 years; based on 889,475 m^3/d (235 MGD) capacity.
[b] Based on current average water production of 529,900 m^3/d (140 MGD).
[c] To determine ¢/m^3 multiply by 0.2642.

than the other alternatives for the same treatment goal, resulting in the lowest total system cost. The GAC contactor system with the EBCT of 15.2 minutes exhibits the next lowest unit cost at 4.41 ¢/m^3 (16.7 ¢/1,000 gal) for this treatment goal. The GAC filter adsorber system given the 1.0 mg/L TOC goal exhibits the highest unit cost at 6.42 ¢/m^3 (24.3 ¢/1,000 gal); a 54% higher cost than the best contactor system. The costs shown in Table 62 indicate that in the case of the CWW for a given treatment goal (TOC = 1.0 mg/L) steel pressure GAC contactors would be more cost-effective than sand replacement GAC filter adsorbers. Also, as expected, less costs are required to meet a less stringent treatment goal (TOC = 1.5 mg/L versus TOC = 1.0 mg/L) because of the longer GAC service life of the less stringent system.

Costs for On-Site Reactivation of the Manchester Water Works GAC

About 1.63 million Kg (3.6 million lbs) of the MWW's carbon was reactivated during a 2 year on-site reactivation research project. Cost data was collected over the two year period which sometimes included intermittent operation. Rather than develop a cost analysis based on intermittent operation, a more representative analysis was made using the data from a period of steady state operation. The operational period used was June 1980 through March 1981 which followed improvements made to the reactivation system. The reactivator uptime operating factor for this period was about 70%. During this 10-month period selected for the cost analysis, MWW reactivated 843,158 Kg (1,857,176 lbs) of carbon.

The capital costs incurred in the research project for the MWW reactivation system are given in Table 63. Table 64 shows a breakdown of the capital costs between equipment related and building related expenses, and the calculation of the depreciation cost used in the on-site and regional reactivation cost analyses. The capital costs associated with the analytical equipment and supplies (Table 63) were not included in the depreciation cost because they are primarily related to research purposes only and not representative of normal operations. Also, the carbon transport system capital expense was not included in the depreciation cost because it was not used during the operational period for which the cost analyses are based.

This semiautomatic carbon transport device was abandoned because of incompatibility with existing filter equipment, faulty new equipment, excessive maintenance, and unacceptable removal of the filter media. A manually operated hose and educator system was utilized.

Table 65 presents a detailed breakdown of the MWW on-site reactivation costs. The costs are based on actual expenses incurred during the selected 10-month period. The table displays the dollar-costs, the amount of resources utilized (i.e., labor manhours, fuel gallons, electric KWH, ...) and the rate at which resources are charged.

TABLE 63. CAPITAL COSTS FOR CARBON REACTIVATION SYSTEM AT MANCHESTER, NH

	Item	Cost
(a)	Carbon Reactivation Building	$ 226,900
(b)	Fluid-Bed System 226.8 kg/hr (500 lbs/hr) Capacity	528,600+
(c)	Carbon Transport System 4 Filters	120,000+
(d)	Analytical Equipment	38,400
(e)	Analytical Supplies (Glassware, Lab, Gasses, Reagents, Etc.)	3,700
(f)	Contractual Services (Architectural & Engineering Fees for Building Design)	25,800
(g)	Personnel Costs (MWW)	22,300*
(h)	Virgin GAC for Test Filter	49,500
(i)	Material Testing Services	7,100
	TOTAL COST	$1,022,300

+Item (b) and (c) both include installation and equipment costs.
*Item (g) does not include overhead costs.

TABLE 64. MANCHESTER WATER WORKS DEPRECIATION CALCULATIONS

Cost	Equipment	Building	Total
A) Construction (Table 63, items a and b)	$528,600	$226,900	$755,500
B) Other Capital (Table 63, items f, g, h, and i)	73,255	31,445	104,700
	$601,855	$258,345	$860,200

Straight Line Depreciation (based on time):

Equipment: Estimated useful life is 15 years.*
Annual depreciation is $601,855/15 = $40,123.7/year.

Building: Estimated useful life is 35 years.*
Annual depreication is $258,345/35 = $ 7,381.3/year.

Total annual depreciation is $40,123.7 + $7,381.3 = $47,505/year.

Estimated Unit Depreciation Cost: (Applicable to regional reactivation)

It is assumed that the effective use of the system is 75% of the time during the year, 24 hrs/day.

Estimated use = .75 x 365 x 24 = 6,570 reactivation hours/year

Unit depreciation cost = $47,505/6,570 = $7.23 per reactivation hour

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Estimated by MWW

TABLE 65. MANCHESTER WATER WORKS REACTIVATION COSTS JUNE 1980 THROUGH MARCH 1981

COST ITEM	TOTAL COST	TOTAL UNITS	UNIT RATES
A) Makeup Carbon	$ 131,349	96,876 kg (213,575 lbs)	$ 1.3558/kg ($0.615/lb)
B) Labor for Reactivation	36,029	4,922 man-hours	$ 7.32/hr
C) Labor for Transportation	5,200	710.4 man-hours	$ 7.32/hr
D) Labor for Lab	929	122.9 man-hours	$ 7.56/hr
E) Labor for Administration	24,515	2,074 man-hours	$ 11.82/hr
F) Parts and Service Calls	49,587	N/A	N/A
G) Fuel Oil	41,415	151 m^3 (40,015 gals)	$ 274.27/m^3 ($1.035/gal)
H) Electrical Power	9,286	175,207 KWH	$ 0.053/KWH
I) Water	13,743	162,064 m^3 (42,813,084 gals)	$ 0.848/m^3 ($0.321/1,000 gals)
J) Lab Supplies	929	N/A	N/A
K) Depreciation	39,587	3,570 reactivation-hours	$ 47,505/yr for 10 months
L) Overhead	51,338	N/A	77% of all MWW labor
TOTAL	$ 403,907		

NOTE: Costs based on reactivation of 843,158 kg (1,857,176 lbs)of GAC; N/A = Not Applicable

The largest single cost item in the economic analysis of on-site GAC reactivation is makeup carbon associated with the GAC losses from reactivation and on-site handling. The GAC makeup expense represents about 33% of the total reactivation system cost. During a period which included five reactivation cycles, MWW experienced total GAC losses of 11.5% by volume. The total overall labor expense (including labor overhead) represents about 29% of the total system cost. The capital cost (depreciation) represents only about 10% of the total system cost.

A summary of the unit costs for the on-site reactivation operation at the MWW is presented in Table 66. Clearly demonstrated is the cost effectiveness of on-site GAC reactivation. Manchester was able to reactivate carbon during the period shown at a total unit cost of 47.87 ¢/kg (21.74 ¢/lb) versus purchasing virgin carbon at a unit cost of 135.42 ¢/kg (61.50 ¢/lb). An explanation of various factors associated with the cost items is presented in the Appendix.

Manchester Water Works Regional Reactivation Costs

Having achieved the initial objective of the project, that being the evaluation of the performance and cost of a full-scale on-site fluid bed GAC reactivation system, future use of the facility for providing regional reactivation service was investigated. The fluid bed GAC reactivator at the MWW has a throughput capacity of approximately 1.63 million kg (3.6 million lbs) of GAC per year, assuming a reasonable operating factor of about 75%. It would take less than 4 months to reactivate the entire 0.45 million kg (1 million lbs) of GAC at the MWW treatment plant, in any given year. The significant excess capacity of the reactivator prompted MWW to explore the feasibility of providing off-site (regional) reactivation to other water utilities in the new England area. An initial regional reactivation effort was undertaken to evaluate the costs and performance of providing a reactivation service to other utilities.

The first step in the regional reactivation effort involved doing a survey of water utilities in New England who use GAC and their estimated reactivation requirements. Nineteen water treatment plants were contacted and all of them expressed interest in the MWW reactivation service. After careful evaluation, a limited regional reactivation program was executed involving three water utilities, namely, (1) Kelseytown, Connecticut Water Company, (2) Danvers, Massachusetts Water Treatment Plant, and (3) Lowell, Massachusetts Water Treatment Plant. Each of the three participating utilities provided approximately 18,160 kg (40,000 lbs) of dry-weight carbon to be transported and reactivated. Prior to starting any reactivation for the two utilities in Massachusetts, the approval of the State Department of Environmental Quality Engineering (DEQE) was necessary. DEQE endorsed this effort and the project began in the fall of 1981.

The vehicle selected for GAC transport was an open top trailer dump truck with a volumetric capacity of 340 m^3 (12,000 ft^3) which corresponds approximately with the capacity of the spent and reactivated storage tanks at MWW. The single transport truck was modified with a watertight tail-gate

TABLE 66. MANCHESTER WATER WORKS REACTIVATION UNIT COSTS

JUNE 1980 THROUGH MARCH 1981

	Cost Item	Cost Per Kg	(Cost Per Lb)
A)	Makeup Carbon	15.59¢	(7.07¢)
B)	Labor for Reactivation	4.28	(1.94)
C)	Labor for Transportation	0.62	(0.28)
D)	Labor for Lab	0.11	(0.05)
E)	Labor for Administration	2.91	(1.32)
F)	Parts and Service Calls	5.87	(2.67)
G)	Fuel Oil	4.92	(2.23)
H)	Electrical Power	1.10	(0.50)
I)	Water	1.63	(0.74)
J)	Lab Supplies and Outside Analyses	0.11	(0.05)
K)	Depreciation	4.70	(2.13)
L)	Overhead	6.08	(2.76)
	TOTAL COST	47.92¢	(21.74¢)

NOTE: Unit costs based on 843,158 kg (1,857,176 lbs) of GAC reactivated.

to ensure that there would be no road spillage. The amount of GAC that could be hauled over the road is governed by state laws which stipulate that the gross weight of the vehicle and load cannot exceed 36,320 kg (80,000 lbs). The empty vehicle weighed 15,890 kg (35,000 lbs), and because the wet-drained GAC weighed roughly twice as much as dry carbon, two separate hauls were required to reactivate the 18,160 kg (40,000 lbs) of dry carbon for each utility.

Loading and off-loading GAC from the truck was accomplished by the hose and eductor system utilized in the earlier MWW on-site reactivation operation. The time required to fill the truck was 4 to 5 hours while off-loading the carbon took about 1.5 to 2.5 hours. The difference in filling time versus emptying time was because a constant flow of carbon was provided to the eductor during emptying and an intermittent flow during the filling operation. Reactivation of 9.080 kg (20,000 lbs) of dry-weight carbon was accomplished in approximately 40 hours. Carbon feed rates, temperatures and pressures varied slightly because of the different grades of GAC and adsorbate loadings.

The first utility that participated in the regional program was the Connecticut Water Company, Kelseytown Treatment Plant located 277 km (172 miles) from MWW. This was followed by Danvers, MA Water Treatment Plant, and Lowell, MA Water Treatment Plant, located 66 and 53 km (41 and 33 miles) from MWW, respectively. All three utilities are conventional water treatment plants using GAC primarily for taste and odor removal. The regional reactivation program was conducted in November and December 1981, and the costs are based on actual expenses incurred during that time.

A summary of the regional GAC reactivation unit costs (¢/lb) for the three participating water utilities is given in Table 67. This table presents for each utility: the total unit cost of regional reactivation service by MWW (including transport) and an estimated unit cost for total spent carbon replacement with virgin GAC. The GAC makeup cost is based on the actual expense to replace carbon lost during GAC reactivation and handling [average of 2,905 kg (6400 lbs) of GAC for each of the three utilities]. The virgin GAC replacement cost refers to the estimated cost associated with replacement of the entire 18,160 kg (40,000 lbs) of spent carbon for each utility. The virgin GAC replacement unit cost is lower than the unit cost of GAC makeup because of the economies of scale inherent in purchasing larger quantities of carbon.

TABLE 67. SUMMARY OF MANCHESTER WATER WORKS REGIONAL REACTIVATION COSTS

Utility	Reactivation* Cost, ¢/lb	Estimated Virgin* GAC Replacement Cost ¢/lb
Connecticut Water Company	66.24	100.7
Danvers, Massachusetts	37.50	63.4
Lowell, Massachusetts	44.95	100.5

*To convert from ¢/lb to ¢/kg divide by 0.454.

The cost of regional reactivation service for the Connecticut Water Company was 145.86 ¢/kg (66.24 ¢/lb) versus complete virgin replacement at 221.74 ¢/kg (100.70 ¢/lb); for Danvers Water Plant regional reactivation was 82.57 ¢/kg (37.50 ¢/lb) versus replacement at 139.60 ¢/kg (63.40 ¢/lb); and for Lowell Water Plant regional reactivation was 98.97 ¢/kg (44.95 ¢/lb) versus replacement at 221.30 ¢/kg (100.50 ¢/lb). Detailed information concerning the regional reactivation effort associated with Connecticut Water Company, Danvers, and Lowell total costs, resources used, and unit costs is presented in the Appendix.

The cost of regional reactivation for Connecticut was found to be considerably higher than the cost for the other two utilities. The two main reasons for this were (1) Connecticut experienced a higher carbon loss along with a high GAC makeup charge rate (242.3 ¢/kg - 111.0 ¢/lb vs 161.4 ¢/kg 73.3 ¢/lb and 251.1 ¢/kg - 114.0 ¢/lb for Danvers and Lowell respectively), and (2) a significantly longer transport distance between Connecticut and Manchester contributed to higher transport equipment and labor costs. The higher carbon losses experienced with the Connecticut GAC were probably because it was a lignite base carbon whereas the Danvers and Lowell carbon was coal base. The total volumetric carbon loss was 23.5% for Connecticut, 15.3% for Lowell, and 11.4% for Danvers.

Comparison of Cincinnati and Manchester Water Works Reactivation Costs

The fluid bed reactivators at Cincinnati and Manchester are rated at the same capacity 227 kg/hr (500 lbs/hr). In examining the on-site reactivation costs, CWW experienced a total unit cost of 50.99 ¢/kg (23.16 ¢/lb) and MWW experienced a total unit cost of 47.87 ¢/kg (21.74 ¢/lb). A direct comparison of all the cost items could not be made between the two systems because some items were defined differently or were not included in the cost analysis. The CWW presented their capital cost as an amortized value (depreciation plus interest), MWW presented capital as depreciation only. The MWW included labor for on-site GAC transport, labor for administration, and labor overhead in the cost analysis while the CWW did not include these items. The CWW reactivation system used natural gas for fuel while MWW used fuel oil. Also, the rates charged on various resources (i.e., $/manhour, $/kwh, $/pound of GAC) varied between the two systems. The most significant factor, however, attributing to CWW's higher reactivation total unit cost was higher GAC losses resulting in higher GAC makeup costs.

SECTION X

COST ESTIMATES FOR VARIOUS TYPES OF GAC SYSTEMS

The information obtained in the CWW and MWW research projects provide many details and insights concerning the cost of operating GAC treatment systems. That information alone, however, cannot provide a basis for evaluating GAC systems of different types and sizes where each of the cost components may incorporate different economies or diseconomies of scale. Therefore, cost estimates for various GAC treatment scenarios are presented here in order to examine the effect of economies of scale in GAC systems and evaluate the cost tradeoffs between alternative GAC treatment systems.

The cost estimates presented in this analysis were generated from preliminary cost estimating functions developed by the Drinking Water Research Division (DWRD) of EPA. These cost functions were derived using data obtained from the CWW and MWW research efforts, previous EPA cost estimating work (Culp/Wesner/Culp), and other published data.(2,4,36-38) Each of the cost functions represent an individual cost item associated with a treatment process, and incorporate one or more design variables and cost parameters. For example, the total O&M cost of a fluid bed reactivation system is estimated by generating and summing the values from seven individual fluid bed cost functions (i.e., reactivation labor, process and building electric, maintenance materials, process fuel, process water, makeup GAC, and labor overhead). The cost estimating functions and assumptions used in this cost analysis are presented in the Appendix.

The costs associated with two types of GAC adsorption systems are examined; deep bed steel pressure GAC contactors, and deep bed concrete gravity GAC contactors. The cost associated with three types of on-site reactivation units are considered; fluid bed, infrared, and multihearth furnaces. An off-site reactivation scenario is also evaluated.

The cost of a concrete gravity contactor system includes the following: contactor system construction; virgin GAC storage construction; construction overhead; initial GAC; contactor system electric, maintenance material, and labor; labor for on-site carbon transport; overhead on labor; water for carbon transport. The cost of a pressure contactor system includes the same items with the addition of the capital, electric, labor, and maintenance material for process pumping. The cost of an on-site reactivation alternative includes the following: reactivation system capital plus overhead; process and building electric; maintenance material; labor; fuel; GAC makeup; water for process; overhead on labor. An off-site carbon transport alternative includes the capital cost for the vehicle(s), the cost of labor for loading and off-loading carbon, fuel cost, maintenance material cost for the truck(s), and assumes the transport of wet-drained carbon. Cost parameters and assumptions used in this analysis are presented in the Appendix.

GAC Treatment Scenarios

Cost estimates for several treatment systems of different size have been generated to examine the difference in cost with variation in system size for the two types of GAC contactor alternatives. Systems with flow capacities of 1, 3, 5, 10, 25, 50, 100, and 175 mgd were evaluated, each having an EBCT of 15 minutes, bed depths of about 3.35 to 3.66 m (11 to 12 ft) and GAC reactivation every three months. System parameters and detailed costs associated with the adsorption process of the pressure contactor and concrete gravity contactor plants are presented in the Appendix. These costs include the capital and O&M expenses associated with the contactors and on-site GAC transport including GAC reactivation. A unit cost summary comparing all the alternatives is presented in Table 68.

Cost Comparison of Adsorption Alternatives

The effect of economies of scale associated with the GAC contactor alternatives (adsorption excluding reactivation) is shown in Figure 66. The smaller systems <37,850 m^3/d (10 mgd) experience significantly higher unit costs than the larger systems. For the steel pressure contactors, the unit cost varies about 6.1 ¢/m^3 (23 ¢/1000 gal) from a 3,785 m^3/d (1 mgd) system to a 94,625 m^3/d (25 mgd) system while there is only a 0.26 ¢/m^3 (1 ¢/1000 gal) unit cost variation from 94,625 m^3/d (25 mgd) to 662,375 m^3/d (175 mgd). For the concrete gravity contactors the unit cost varies about 4 ¢/m^3 (15 ¢/1000 gal) from 3,785 m^3/d (1 mgd) to 94,625 m^3/d (25 mgd) while the variation in cost is about 0.26 ¢/m^3 (1 ¢/1000 gal) from 94,625 m^3/d (25 mgd) to 662,375 m^3/d (175 mgd). Comparing the alternative adsorption systems, it appears that the steel pressure contactor systems exhibit higher costs (about 1.5 to 3.7 ¢/m^3 - 6 to 14 ¢/1000 gal) than the concrete gravity contactor systems in all cases. The concrete gravity systems exhibit lower capital and O&M costs than the steel pressure systems as a result of the greater economies of scale inherent in a fewer number of larger-sized concrete contactors compared with a larger number of smaller-sized steel contactors.

Cost Comparison of On-site Reactivation and Replacement Alternatives

The on-site reactivation alternatives exhibit economies of scale similar in nature to that of GAC contactors with systems smaller than 94,625 m^3/d (25 mgd) experiencing significantly higher unit costs than the larger systems (Figure 67). Infrared reactivation appears to be the least expensive alternative for smaller plants (<56,775 m^3/d - 15 mgd) while fluid bed reactivation is cheaper for larger systems. Regardless of which technology is used, on-site reactivation is cheaper than replacement of spent carbon with virgin GAC. Even with a 11,355 m^3/d (3 mgd) system, on-site reactivation appears to be more cost-effective.

TABLE 68. UNIT COST ESTIMATES FOR VARIOUS GAC SYSTEMS

Item		GAC SYSTEM (mgd)[a]						
	1	3	5	10	25	50	100	175
Pressure contactors (¢/1,000 gal)[b]	35.20	19.83	17.75	16.15	11.94	11.32	10.97	10.87
Concrete gravity contactors (¢/1,000 gal)	21.16	11.27	8.76	8.16	5.70	4.98	4.77	4.58
Fluid bed reactivation (¢/lb)[c]	-	85.64	64.22	46.34	33.50	28.00	27.30	25.99
Infrared reactivation (¢/lb)	-	64.27	53.55	44.20	36.78	33.09	32.39	31.33
Multihearth reactivation (¢/lb)	-	91.92	81.35	60.84	45.85	39.04	38.35	36.76
Virgin Replacement (¢/lb)	118.38	109.98	106.28	101.46	95.42	91.08	86.96	83.75
Pressure Contactors								
with fluid bed ¢/lb	-	59.04	47.15	37.36	27.26	24.14	23.46	22.76
with infrared ¢/lb	-	49.25	42.27	36.38	28.76	26.48	25.79	25.20
with multihearth ¢/lb	-	61.91	54.99	44.00	32.91	29.20	28.51	27.69
Concrete Gravity Contactors								
with fluid bed ¢/lb	-	50.48	38.16	29.37	21.02	17.80	17.26	16.47
with infrared ¢/lb	-	40.69	33.28	28.39	22.52	20.14	19.59	18.92
with multihearth ¢/lb	-	53.35	46.00	36.01	26.67	22.86	22.31	21.40

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[a] mgd x 3,785 = m^3/d
[b] ¢/1000 gal x 0.2642 = ¢/m^3
[c] ¢/lb x 2.2 = ¢/kg

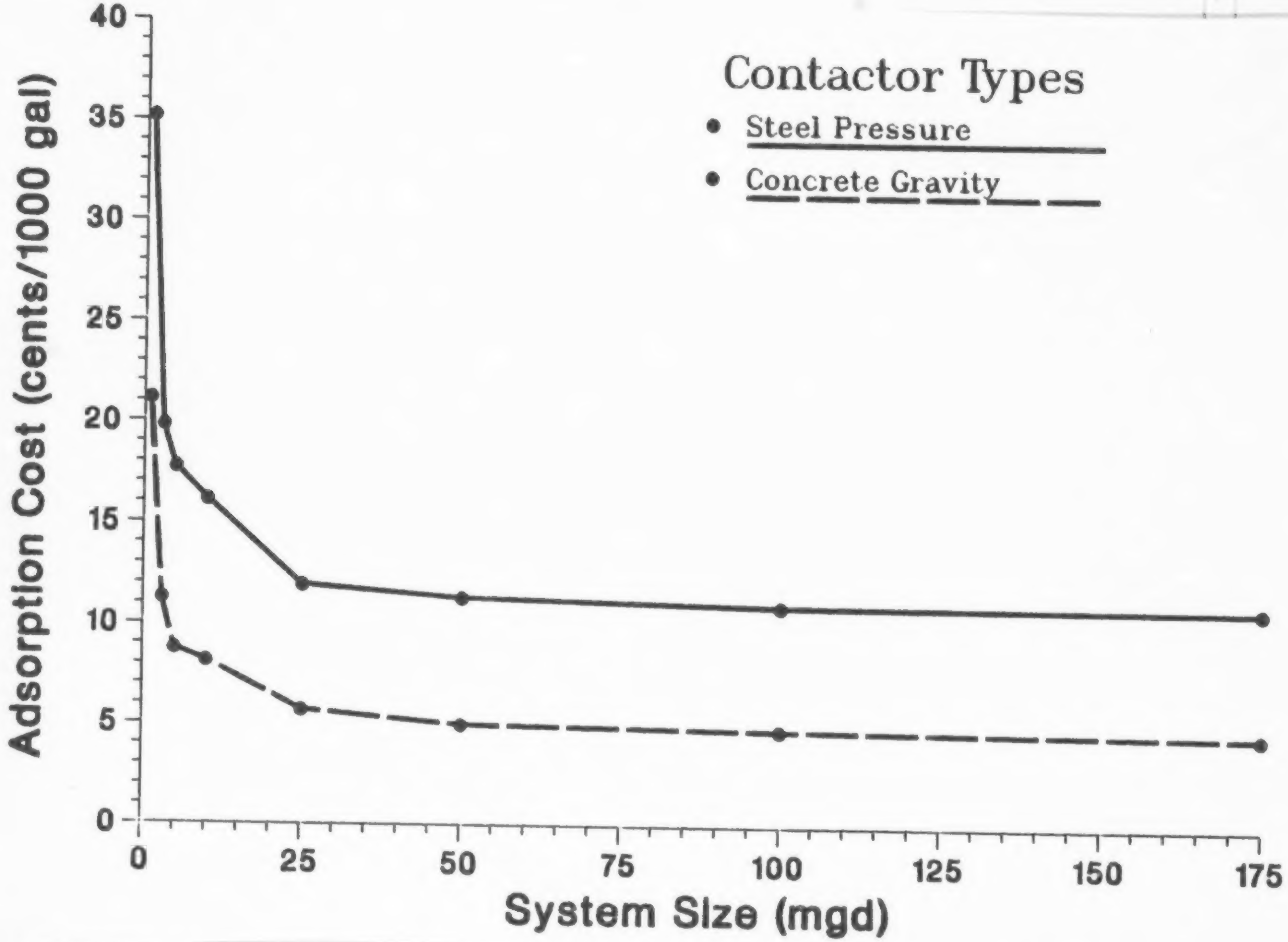


FIGURE 66. GAC CONTACTOR COST (¢/1,000 gal X 0.2642 = ¢/m^3;mgd X 3,785 = m^3/d)

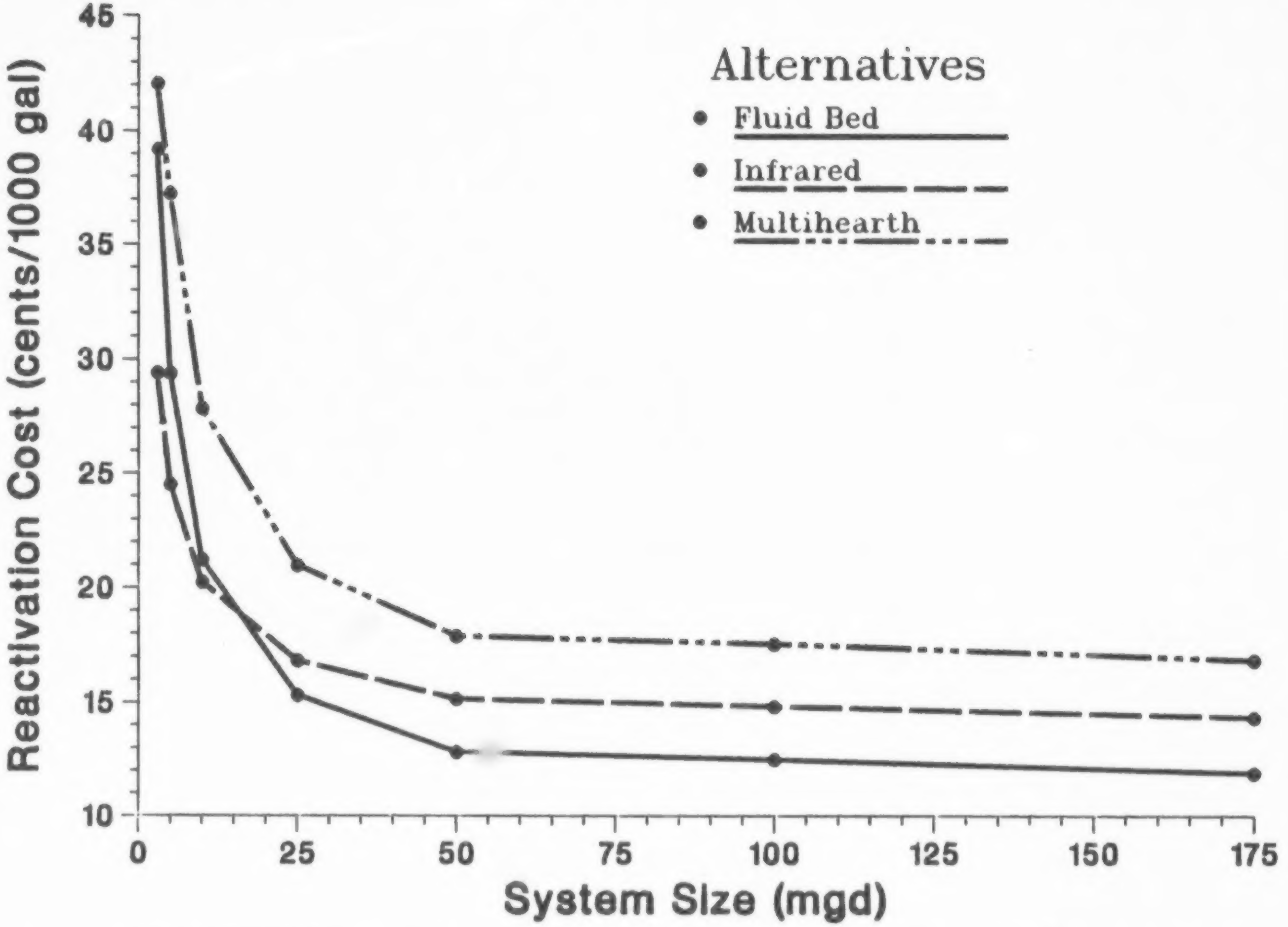


FIGURE 67. GAC REACTIVATION COST (¢/1,000 gal X 0.2642 = ¢/m^3;mgd X 3,785 = m^3/d)

The cost tradeoffs between on-site reactivation and replacement of spent carbon with virgin GAC are shown in Figures 68 and 69. Figure 68 presents the total costs ($/year) of single fluid bed, infrared, and multihearth furnace systems compared to complete GAC replacement, as a function of the amount of carbon to be reactivated or replaced. The reactivation costs include increased furnace capacity to incorporate a 70% up-time operating factor. The figure shows that even for very small amounts of carbon, i.e., 136,200 kg (300,000 pounds)/yr, a small infrared reactivation furnace, i.e., rated 22.7 kg (50 lbs) hour, appears to be more economical than replacement of spent carbon with virgin GAC. For larger amounts of carbon, on-site reactivation becomes increasingly more cost-effective (Figure 69).

The cost tradeoffs between the three reactivation furnaces are shown in Figure 70. This figure presents the unit costs of single individual fluid bed, infrared, and multihearth reactivators as a function of the amount of carbon to be reactivated. Infrared reactivation appears to be the most economical reactivation alternative for amounts of carbon less than about 908,000 kg (2,000,000 pounds)/yr. Above that amount, fluid bed reactivation is the most economical. This breakeven point between infrared and fluid bed reactivation, however, is highly dependent on factors such as labor rates, fuel rates, electrical power rates, assumed up-time operating factors, etc.

Total Cost of Various GAC Treatment Systems

The costs presented in Table 68 assume an EBCT of 15 minutes and a reactivation frequency of every 3 months. These costs may vary significantly with variations in EBCT, reactivation frequency, hydraulic loading, size of contactors, and other system parameters. As an example, Figures 71 and 72 present the total GAC treatment unit cost adsorption plus on-site reactivation associated with concrete gravity and steel pressure contactor systems for 37,850 m^3/d (10 mgd) and 378,500 m^3/d (100 mgd) plants, as a function of reactivation frequency, with EBCT of 15 and 20 minutes. In general, the figures show the following:

(a) the 378,500 m^3/d (100 mgd) plant exhibits lower unit water production costs than the 37,850 m^3/d (10 mgd) plant because of the greater economies of scale inherent in larger facilities;

(b) systems requiring more frequent reactivation for a given plant size exhibit higher unit water production costs;

(c) the unit water production costs associated with the systems having the higher EBCT values (i.e., 20 minutes) for a given plant at a fixed reactivation frequency are higher, because larger facilities are required and larger volumes of carbon must be reactivated, thus increasing the costs.

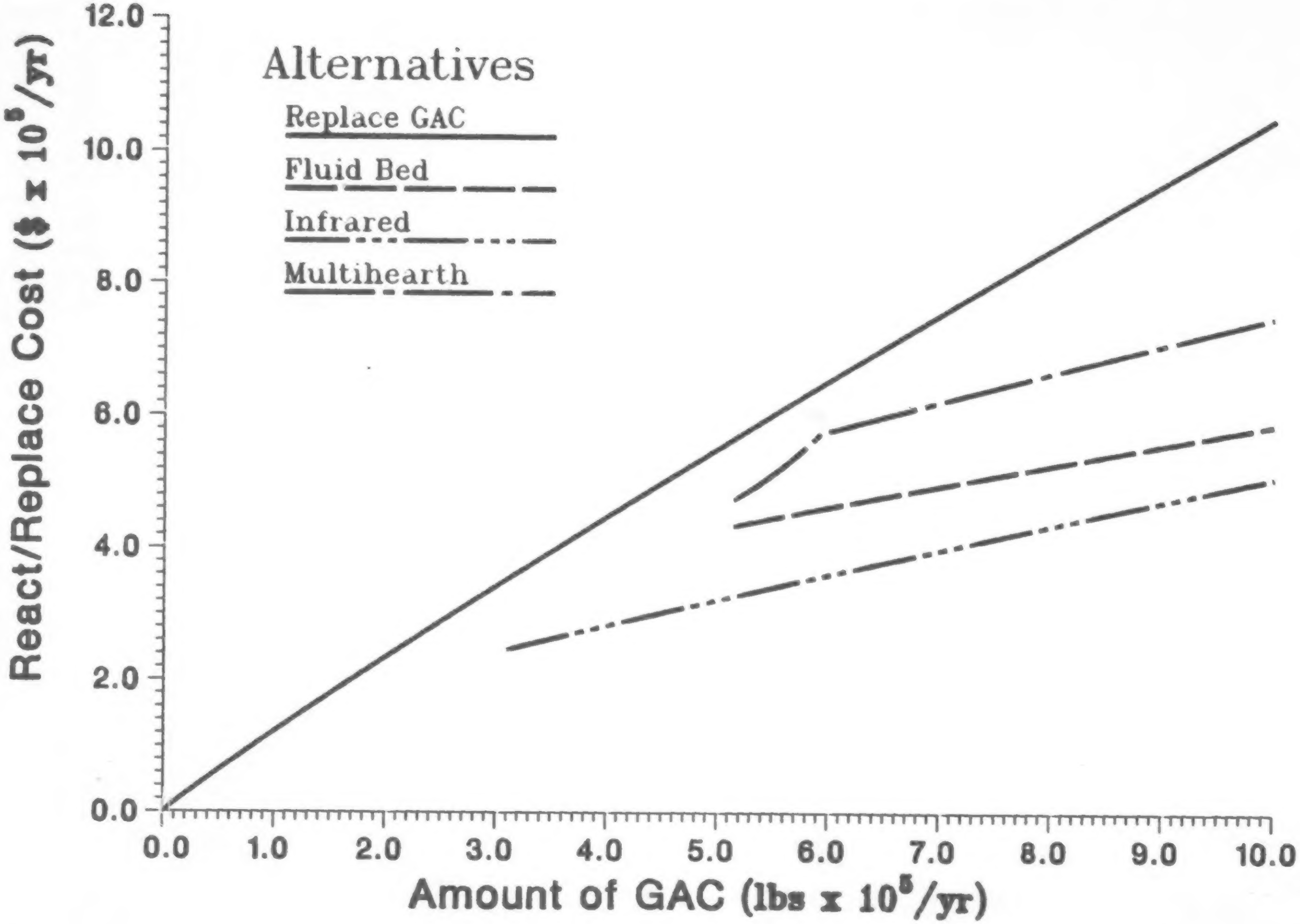
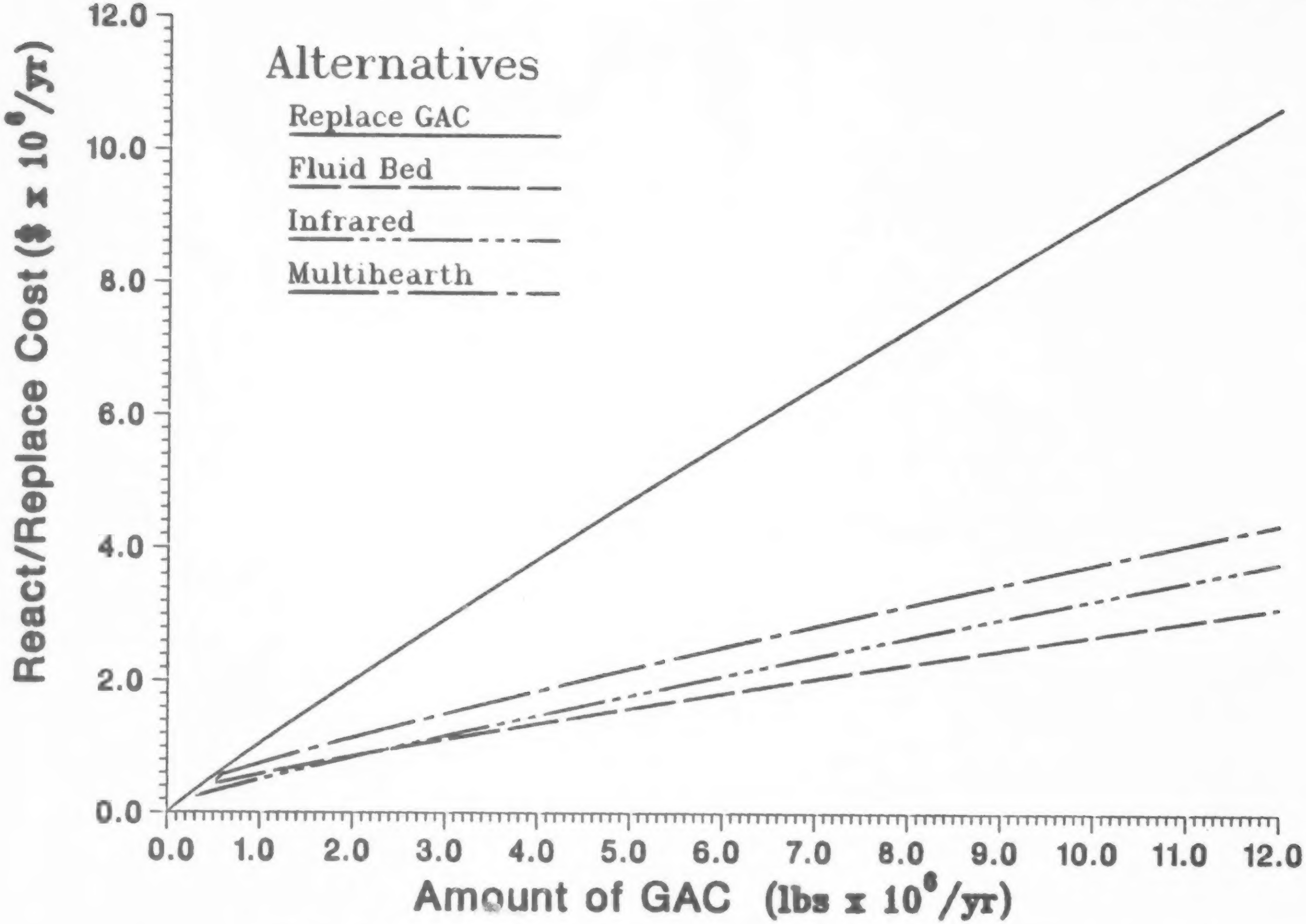


FIGURE 68. GAC REACTIVATION AND REPLACEMENT COST
(lbs/yr X 0.454 = kg/yr)



Amount of GAC (lbs x 10^6/yr)

FIGURE 69. ON-SITE REACTIVATION VERSUS GAC REPLACEMENT

(lbs/yr X 0.454 = kg/yr)

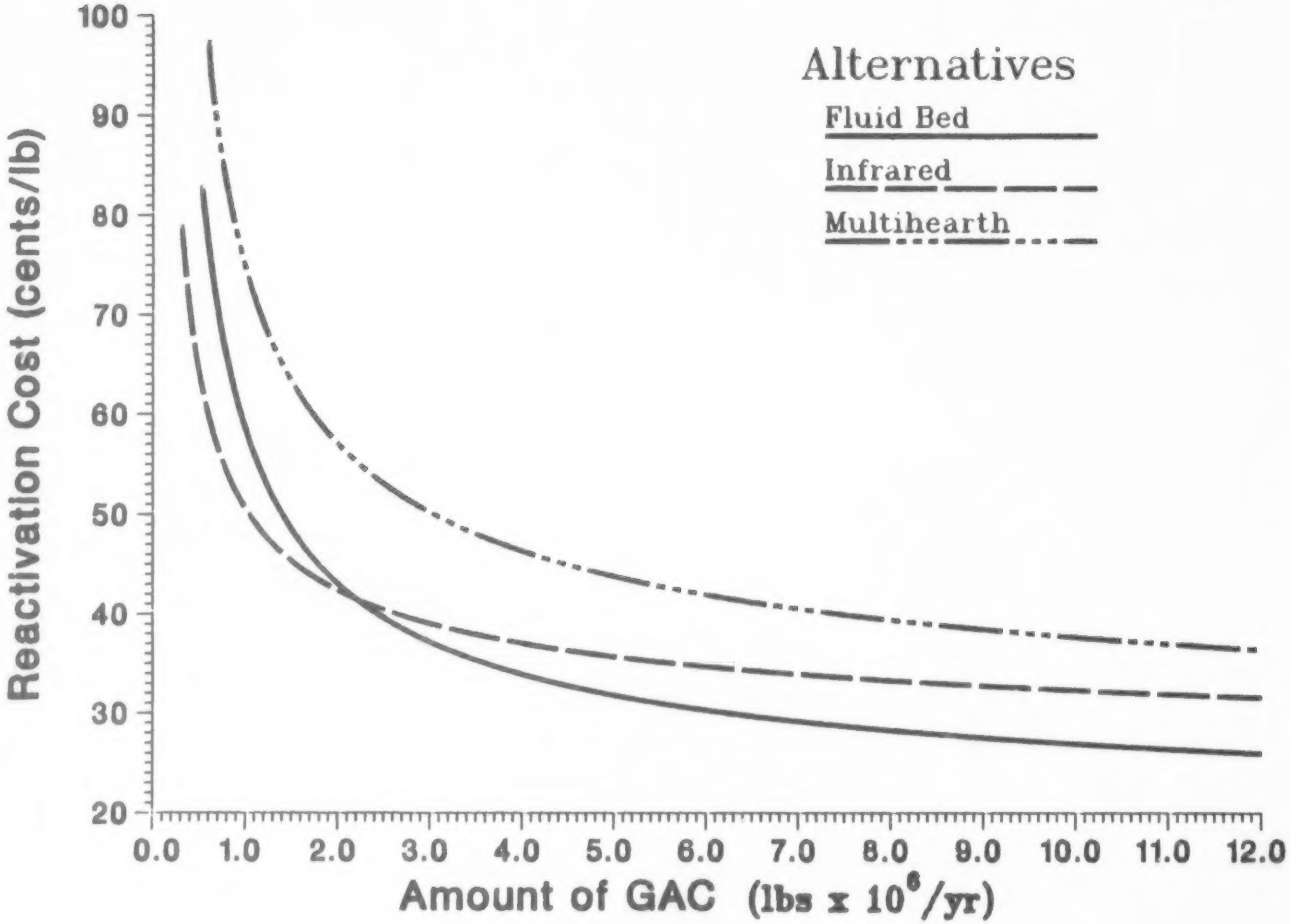


FIGURE 70. REACTIVATION COST FOR THREE FURNACE TYPES
(¢/lb X 2.2 = ¢/kg; lbs/yr X 0.454 = kg/yr)

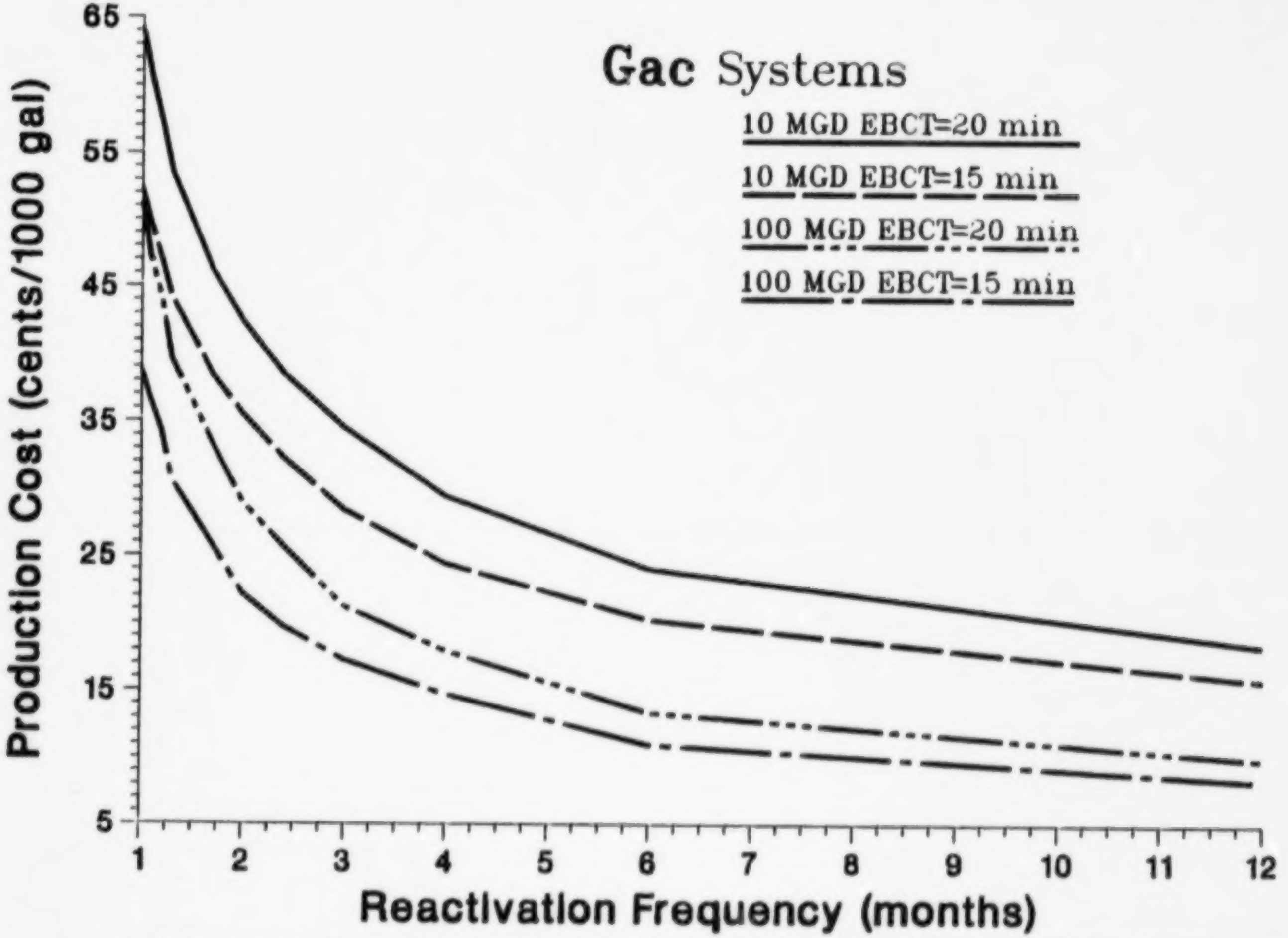


FIGURE 71. COST OF CONCRETE GRAVITY CONTACTORS WITH REACTIVATION AS A FUNCTION OF REACTIVATION FREQUENCY AND EBCT (¢/1,000 gal X 0.2642 = ¢/m^3;mgd X 3,785 = m^3/d)

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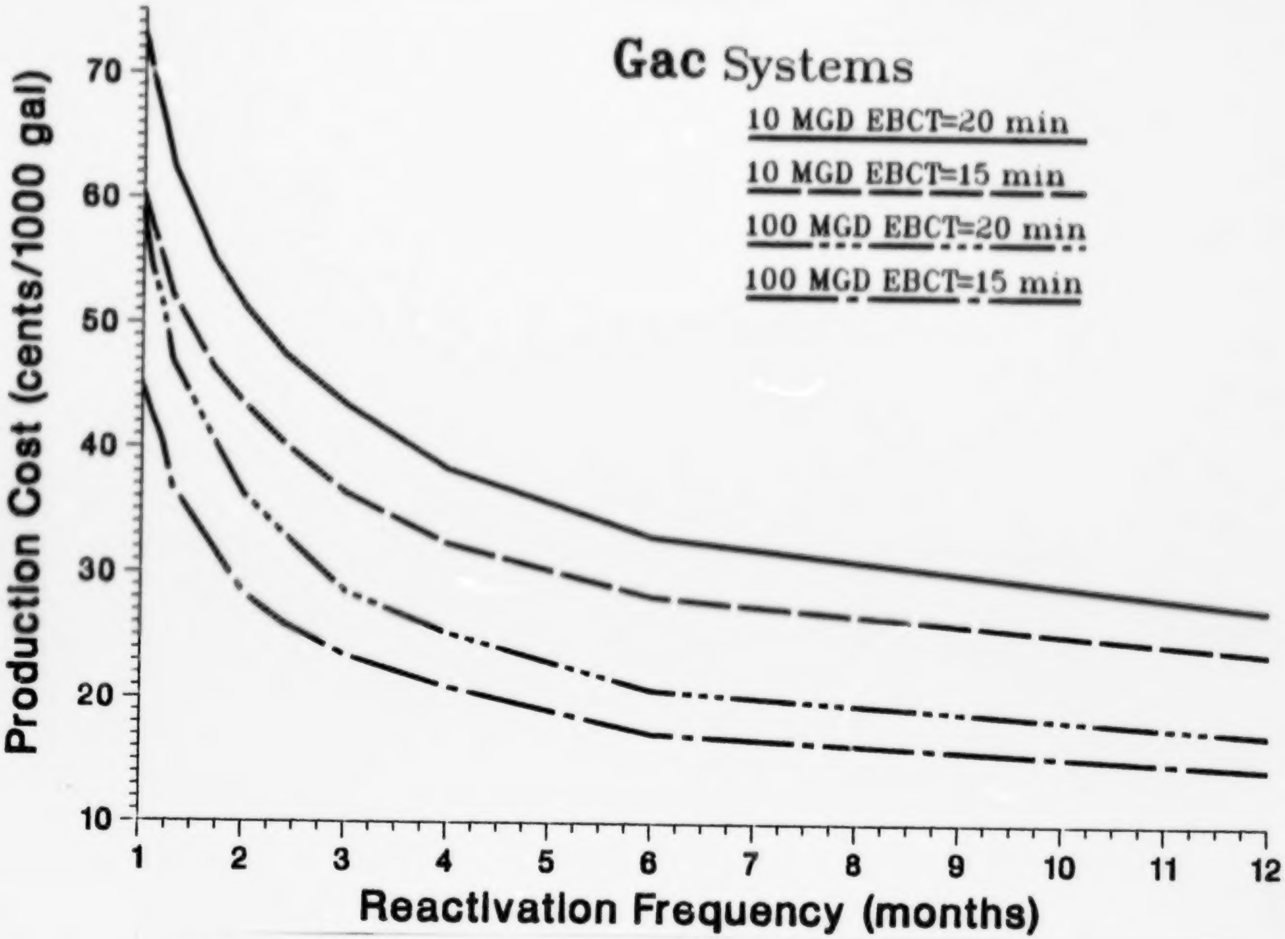

FIGURE 72. COST OF PRESSURE CONTACTORS WITH REACTIVATION AS A FUNCTION OF REACTIVATION FREQUENCY AND EBCT (¢/1,000 gal X 0.2642 = ¢/m^3;mgd X 3,785 = m^3/d)

Regional Reactivation Versus On-Site Reactivation and GAC Replacement

The cost information presented earlier showed that even for small amounts of GAC (i.e., 136,200 kg - 300,000 pounds year) on-site reactivation is more economical than replacement of spent carbon with virgin GAC. For systems using smaller amounts of GAC, off-site reactivation may be a cost-effective alternative to virgin replacement, and regional reactivation may be more economical than on-site reactivation for some larger utilities. As an example, the scenario presented earlier for several utilities of varying size is extended here to evaluate a regional reactivation alternative. This regional reactivation system consists of 3,785; 11,355; 18,925; 37,850; 94,625 m^3/d (1, 3, 5, 10, and 25 mgd) plants using off-site reactivation at a 378,500 m^3/d (100 mgd) plant. The one-way travel distance for each of the utilities using off-site transport is 121 km (75 miles). Four trucks are utilized, each having a haul capacity of 9,080 kg (20,000 lbs) of wet-drained GAC, and each costing $75,000 depreciated over 10 years.

Reactivation frequency is based on every 3 months, with total GAC losses of 18% (15% reactivation + 3% transport). Two fluid bed reactivators each having a capacity of 21,565 kg (47,500 lbs)/day were utilized at the 378,500 m^3/d (100 mgd) plant. The annual costs associated with the regional reactivation scenario are presented in Table 69. Table 70 presents a unit cost summary comparing the costs for regional reactivation, on-site reactivation, and replacement with virgin GAC for each of the utilities.

In this scenario, regional reactivation is the most economical alternative for all the utilities. Even with the addition of transport capital and O&M expenses and increased GAC makeup cost (resulting from assumed higher losses), the economies of scale inherent in the larger regional reactivation facilities are great enough to off-set the additional costs and make the regional system more cost-effective than the on-site systems. The greatest cost savings from participating in the regional system are exhibited by the smaller utilities <37,850 m^3/d (10 mgd) plants as they take greater advantage of the economies of scale inherent in the relatively larger regional facilities. The larger-sized utilities >37,850 m^3/d (10 mgd) plants take significantly less advantage of the economies of scale because the change in scale between on-site facilities and the regional facilities is much smaller. Thus the larger utilities exhibit less cost savings by participating in the regional system compared to on-site systems. However, the costs presented here are based on allocation by proportional use of the system. If another cost allocation method is used, the larger utilities may realize greater cost savings from the regional system.

TABLE 69. COSTS ASSOCIATED WITH REGIONAL REACTIVATION SCENARIO

System (mgd)[a]	GAC Amount (lbs/yr)[b]	Transport O&M ($/yr)	Transport Capital ($/yr)	Makeup GAC ($/yr)	Furnace O&M and Capital ($/yr)	Total Cost ($/yr)	Unit Cost (¢/lb)
1	167,194	3,679	683	39,965	18,062	62,389	37.31
3	501,214	11,190	2,046	111,311	54,148	178,695	35.65
5	835,356	18,777	3,411	179,275	90,246	291,709	34.92
10	1,670,712	37,906	6,821	342,281	180,492	567,500	33.96
25	4,173,300	95,863	17,039	804,123	450,854	1,367,879	32.77
100	6,696,620	0	0	2,473,156	1,803,786	4,276,942	25.61
Total GAC	24,044,396						

[a] mgd x 3,785 = m^3/d
[b] lbs/yr x 0.454 = kg/yr
[c] ¢/lb x 2.2 = ¢/kg

TABLE 70. UNIT COST SUMMARY OF REGIONAL ALTERNATIVES IN SCENARIO

	GAC System (mgd)[a]					
	1	3	5	10	25	100
	(¢/lb of GAC)[b]					
Regional reactivation	37.31	35.65	34.92	33.96	32.77	25.61
On-site reactivation	-	64.27	53.55	44.20	33.50	27.30
Replacement, virgin GAC	118.38	109.98	106.28	101.46	95.42	86.96

[a] mgd x 3,785 = m^3/d
[b] ¢/lb x 2.2 = ¢/kg

SECTION XI

SUMMARY OF COST

The cost information presented in this report cannot characterize all the costs that may be experienced in all real-life GAC treatment scenarios. This report, however, presents many insights into GAC treatment costs as experienced by the Cincinnati Water Works and Manchester Water Works. General characteristics of GAC adsorption costs for steel pressure and concrete gravity contactors, on-site reactivation using fluid bed, infrared, and multihearth furnaces, off-site reactivation costs, behavior of GAC treatment costs with variations in system size, and the cost relationships associated with several GAC treatment alternatives are described.

In conclusion, the cost evaluation of GAC treatment shows the following:

(a) Concrete gravity GAC contactor systems appear to exhibit lower water production costs than steel pressure GAC contactor systems, given the same water treatment goal. The concrete systems take greater advantage of the economies of scale inherent in a fewer number of larger-sized contactors compared to a larger number of smaller-sized steel contactors.

(b) The Cincinnati Water Works research study showed that a full-scale deep-bed steel pressure GAC contactor system appears to be more economical than a conventional-depth sand replacement GAC filter adsorber system, given the same water treatment goal. The filter adsorber system with a lower EBCT would be required to reactivate more frequently and incur significantly higher costs.

(c) Infrared reactivation appears to be more economical than fluid bed and multihearth reactivation for small quantities of carbon required. For quantities of carbon greater than about 908,000 kg (2,000,000 lbs)/yr fluid bed reactivation appears to be the most cost-effective alternative.

(d) On-site reactivation appears to be more economical than replacement of spent carbon with virgin GAC for amounts of carbon as small as 136,200 kg (300,000 lbs)/yr using a 22.7 kg (50 lbs) hour infrared furnace. For larger quantities of carbon, on-site reactivation becomes increasingly more cost-effective.

(e) For amounts of carbon smaller than what would be economical for on-site reactivation, off-site regional reactivation may be a cost-effective alternative to replacement of spent carbon with virgin GAC. Also, for some utilities in which on-site reactivation is cost-effective, regional reactivation may be a more economical alternative.

(f) The GAC adsorption and reactivation process costs exhibited significant economies of scale. In the scenario presented, total water production unit costs (adsorption plus reactivation) for 11,355 m^3/d (3 mgd) and 662,375 m^3/d (175 mgd) plants respectively ranged from about 13.2 ¢/m^3 (50¢/1000 gal) to about 6.1 ¢/m^3 (23¢/1000 gal)for steel pressure contactor systems and about 10.8 ¢/m^3 (41¢/1000 gal) to about 4.5 ¢/m^3 (17¢/1000 gal) for the concrete gravity contactor systems.

SECTION XII

PREDICTION OF GAC LOADING CAPACITY FOR TOTAL ORGANIC CARBON

Background

Various mathematical models have been developed for the prediction of GAC adsorptive capacity. Such models are frequently utilized to simulate batch adsorption experiments for single- and bi-solute systems.(39-44) Typically, certain equilibrium expressions and constants are either estimated or calculated for a particular adsorbate-GAC combination. The equilibrium adsorption isotherms so determined are often extrapolated to predict full scale GAC adsorber or contactor performance.

Recently, an alternative strategy has been applied to model the adsorption capacity characteristics of three full scale GAC systems which were operated in Evansville, IN, Manchester, NH and Cincinnati, OH over 3 to 4 month spans of time in drinking water treatment trains. In addition to variation in carbon type and physical properties, the GAC systems were also reactivated several times to allow investigation of capacity renewal or reduction. For each phase of operation of a particular GAC system, the total GAC loading was calculated over time and a model function was subsequently fit to the loading curves by a non-linear least squares regression procedure.(45) The model function is of the following form:

$$Y(t) = \frac{C}{1 + K\,e^{-Rt}} \qquad \text{[Eq. 1]}$$

where:

Y(t) = milligrams of solute adsorbed per kg carbon
t = runtime (i.e., elasped time from start of run phase in days)

The values of the parameters C, R, and K in Equation 1 were solved iteratively to provide the best "fit" of the model function to the actual loading vs. runtime profiles. The parameter C is interpreted as the limiting value for the GAC capacity (mg solute adsorbed/kg GAC/day). In practice, this limiting value of C was typically reached within 90 days. This equation provides an adequate description of the actual GAC loading curves for TOC in both the filter adsorbers and contactors studied.

Use of Predictive Model

Values of the "best fit" parameters C, R and K were calculated for each of 15 case runs (see appendix for description of study cases). A search was then made for statistically significant and physically meaningful numerical relationships between the fitted C, R and K parameters and experimentally determined properties of a given GAC system. When such relationships were found, measurements of certain physio-chemical properties of the system were used as independent variables in a regression analysis to predict values of C, R and K. Lastly, a graphical comparison was made between the computer fitted model estimates for C, R and K with those predicted from experimental measurements and associated regression derived equations.

Table 71 displays all pertinent GAC data that was available from the research projects mentioned above. The choice of which variables to include in a regression analysis for a particular parameter were based on statistically significant correlation coefficients selected from a main correlation matrix. "APS_TOC" is the slope of the best fit linear regression line which can be fit through a plot of the actual cumulative TOC applied to the carbon (mg TOC/kg GAC) vs. runtime (days). The presumption of a linear relationship for the variance of APS_TOC with time was valid in all model cases studied. Transient spikes in influent concentration tended to average out and result in only trivial reductions in the linear regression correlation coefficients.

The iodine number and molasses decoloring index provide an indication of the quantity of small and large pores, respectively. In general, smaller pores possess a greater affinity for low molecular weight organics whereas larger pores possess a greater affinity for higher weight organics. The EBCT was adjusted for each particular contactor or adsorber to provide a predetermined TOC removal. This typical value for TOC was around 1.0 mg/l for the GAC effluent. Contact times varied from 7 minutes to 30 minutes in the model cases presented. GAC depth varied from 76 to 457 cm (30-180 in). Because particle diameter decreases with subsequent carbon reactivations, a unitless surrogate variable "PDRATIO" was created to account for the number of reactivation cycles.

$$\text{PDRATIO} = \frac{\text{mean particle diameter of reactivated GAC (mm)}}{\text{mean particle diameter of virgin GAC (mm)}} \qquad \text{[Eq. 2]}$$

Prediction of C

The most reasonable causal variables to include in an analysis of variance of C, the so-called total "capacity" parameter are related to GAC surface area, pore-size, particle diameter, EBCT, depth and mesh size. Also, a frequently employed technique for determining the total surface area of a GAC sample (m^2/g) is the Brunauer Emmett Teller (BET) isotherm which measures the amount of nitrogen gas which can be adsorbed by the GAC sample. Although the BET isotherm yields valuable surface area data

TABLE 71. INPUT DATA FOR PREDICTIVE GAC LOADING MODEL

ACTUAL RESEARCH DATA

STUDY CASE #	APS-TOC (mg/l/day) $\cdot 10^{-4}$	IODINE # (mg/g)	MOLASSES # (DI/g)	EBCT (min)	MESH SIZE (mm^2)	DEPTH (cm)
1	9.48	1184	10.50	7.48	480	76
2	13.21	1128	13.50	7.48	480	76
3	9.48	1103	15.00	7.48	480	76
4	7.39	1104	15.00	7.48	480	30
5	3.53	1128	9.60	15.23	480	457
6	5.18	1096	11.00	15.23	480	457
7	8.57	617	18.50	9.60	300	198
8	7.49	638	17.80	9.60	300	198
9	5.48	439	10.20	9.60	300	198
10	5.96	596	14.70	9.60	300	198
11	8.79	650	13.70	9.60	300	198
12	3.06	911	-	26.40	240	122
13	3.26	803	4.85	26.40	240	122
14	5.34	896	4.80	26.40	240	122
15	3.79	1073	5.30	26.40	240	122

CALCULATED DATA

	Fitted			
STUDY CASE #	K	C	R	PDRATIO
1	5.576	0.03121	0.04598	1.000
2	9.123	0.02879	0.13750	0.931
3	7.767	0.02001	0.13040	0.815
4	7.500	0.02336	0.08045	0.719
5	10.620	0.06451	0.01757	1.000
6	9.382	0.04022	0.05443	0.948
7	5.490	0.02601	0.07948	1.000
8	6.164	0.02481	0.07587	0.884
9	7.008	0.01717	0.06535	1.000
10	8.003	0.01852	0.08026	0.941
11	14.300	0.02279	0.19220	-
12	6.740	0.01526	0.03760	1.000
13	6.949	0.02169	0.03737	1.000
14	6.825	0.02400	0.06463	0.923
15	9.235	0.01840	0.06305	0.885

for a GAC sample, combinations of other variables could adequately account for the variance in C. In practice, the BET isotherm is expensive and inconvenient to perform on-site, relative to the iodine number determination which is sometimes utilized as a measure of reactivation efficacy. Another surrogate variable (mesh size) was also incorporated to account for bulk analysis properties of the GAC sample. This variable is the product of the screen dimensions (i.e. 12 x 40 mesh is represented as 480 in the input data). The final best-fit stepwise regression analysis for C as a function of particular GAC physio-chemical properties is given in the Appendix.

Prediction of R

The graphic representation of equation 1 is typically an elongated "S" shaped curve, the steepness of which is governed by the exponential in the denominator; as the parameter R increases so does the slope of the curve. Intuitively, it is expected that as the rate of applied solute increases on the carbon bed or column, the curve which describes the GAC's approach to saturation (total loading capacity) will become more steep. Indeed, the slopes of the curves do increase and the majority of the variance in R is accounted for by the slope of the applied solute concentration versus time (APS_TOC). As PDRATIO decreases, implying increased number of reactivation cycles, R increases though the effect is statistically insignificant relative to the effect of the variable APS_TOC.

Prediction of K

A visual comparison of model study case 1 with case 5 illustrates the predominant effect of the parameter K on loading curve profiles (Figures 73 and 77). Case 5 is representative of a GAC system where initial loading is relatively slow. The calculated value of K is about twice as large in case 5 as compared to case 1. Increasing the parameter K in Equation 1 tends to shift the model function curve to the right on the abcissa. This effect is observed in both pilot and full scale column breakthrough profiles as GAC depth is increased. In addition to a correlation with GAC bed depth, K is also highly correlated with the parameter R. Stepwise regression of K against all other model variables indicated that the variance in K was explained adequately as a function of R and bed depth. It should be noted that mechanistically one must calculate the R parameter (via linear regression against APS_TOC) before the K parameter can be determined.

The resulting model equations for C, R and K are summarized in the Appendix. The general linear regression calculations used in this work were performed with a standard statistical procedure.(46) The theoretically predicted loading curves over representative time spans were generated from equation 1 after mathematical determination of the values of C, R and K as functions of certain GAC properties and rate of applied TOC. Figures 73 through 85 display the actual GAC loading data, the numerical curve fit of the model equation to the actual data and the theoretically predicted loading curve. Case 11 and case 12 were not modeled because some data were missing.

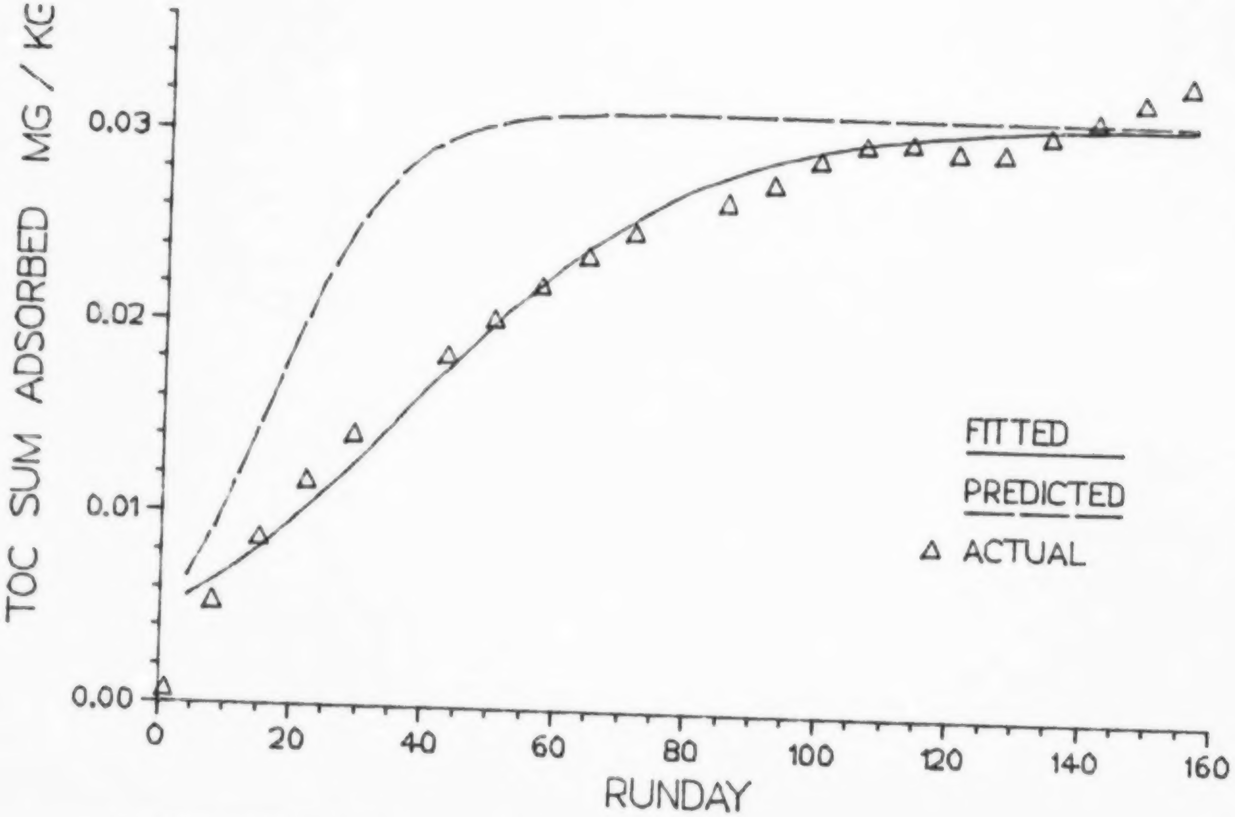

FIGURE 73. MODEL STUDY CASE 1.
LOADING CURVES FOR GAC FILTER ADSORBER, VIRGIN GAC – CINCINNATI, OH.

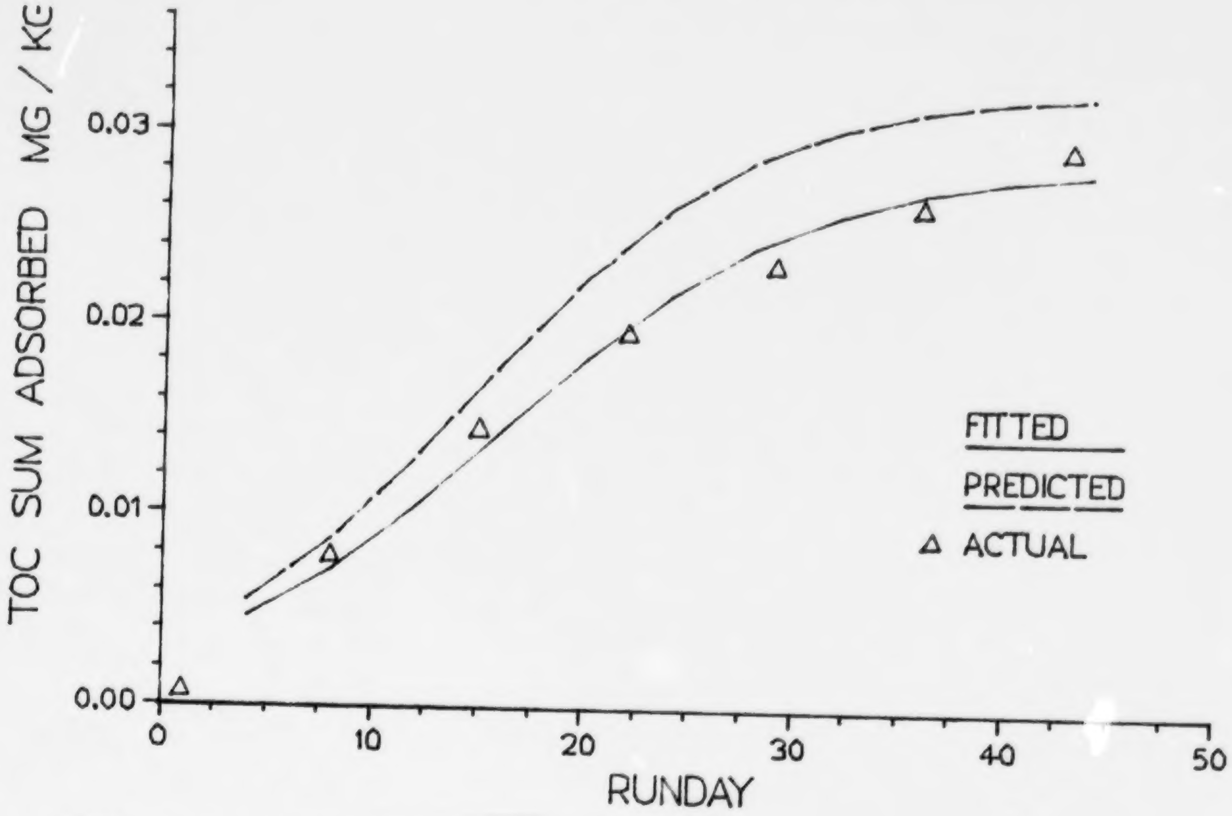

FIGURE 74. MODEL STUDY CASE 2.
LOADING CURVES FOR GAC FILTER ADSORBER, FIRST REACTIVATION – CINCINNATI, OH.

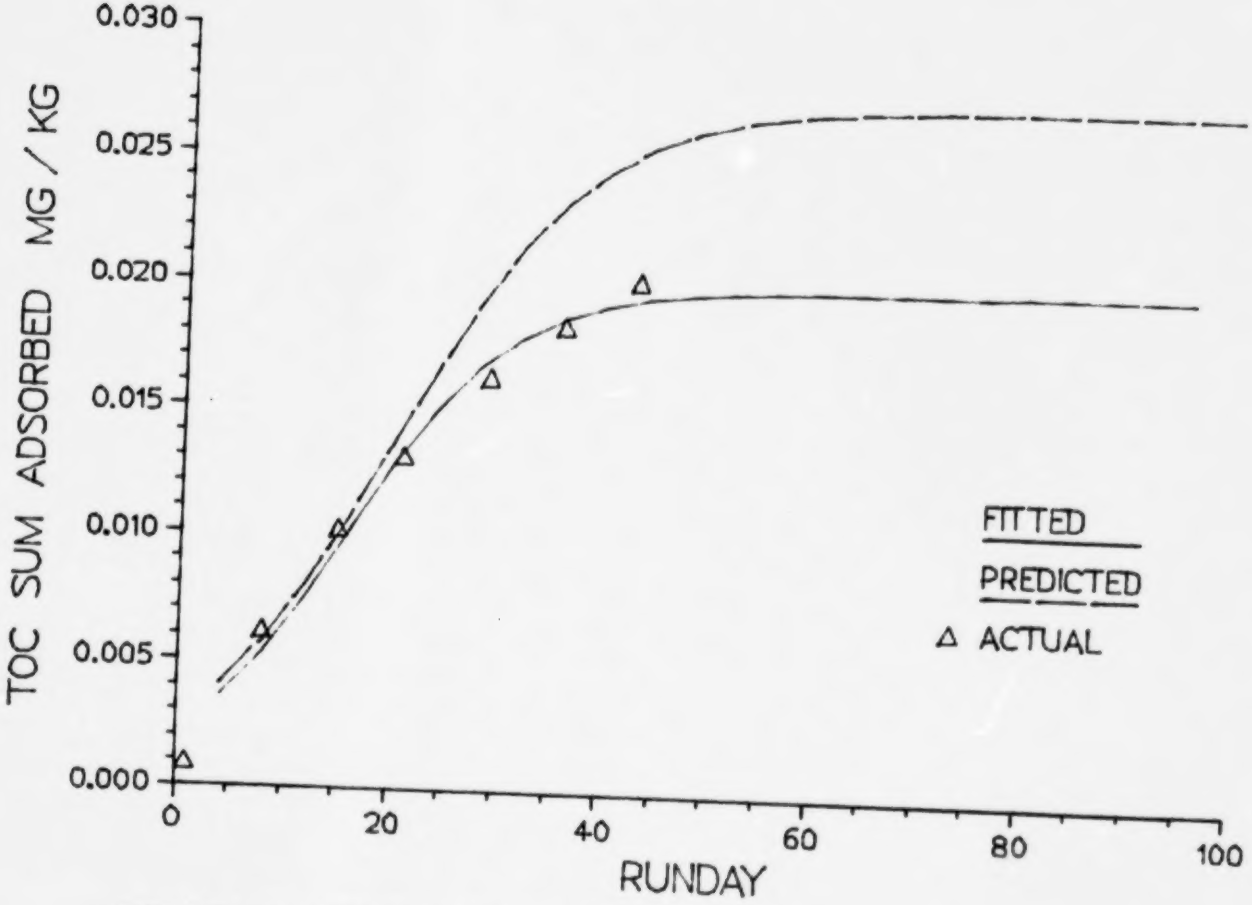

FIGURE 75. MODEL STUDY CASE 3.
LOADING CURVES FOR GAC FILTER ADSORBER, SECOND REACTIVATION — CINCINNATI, OH.

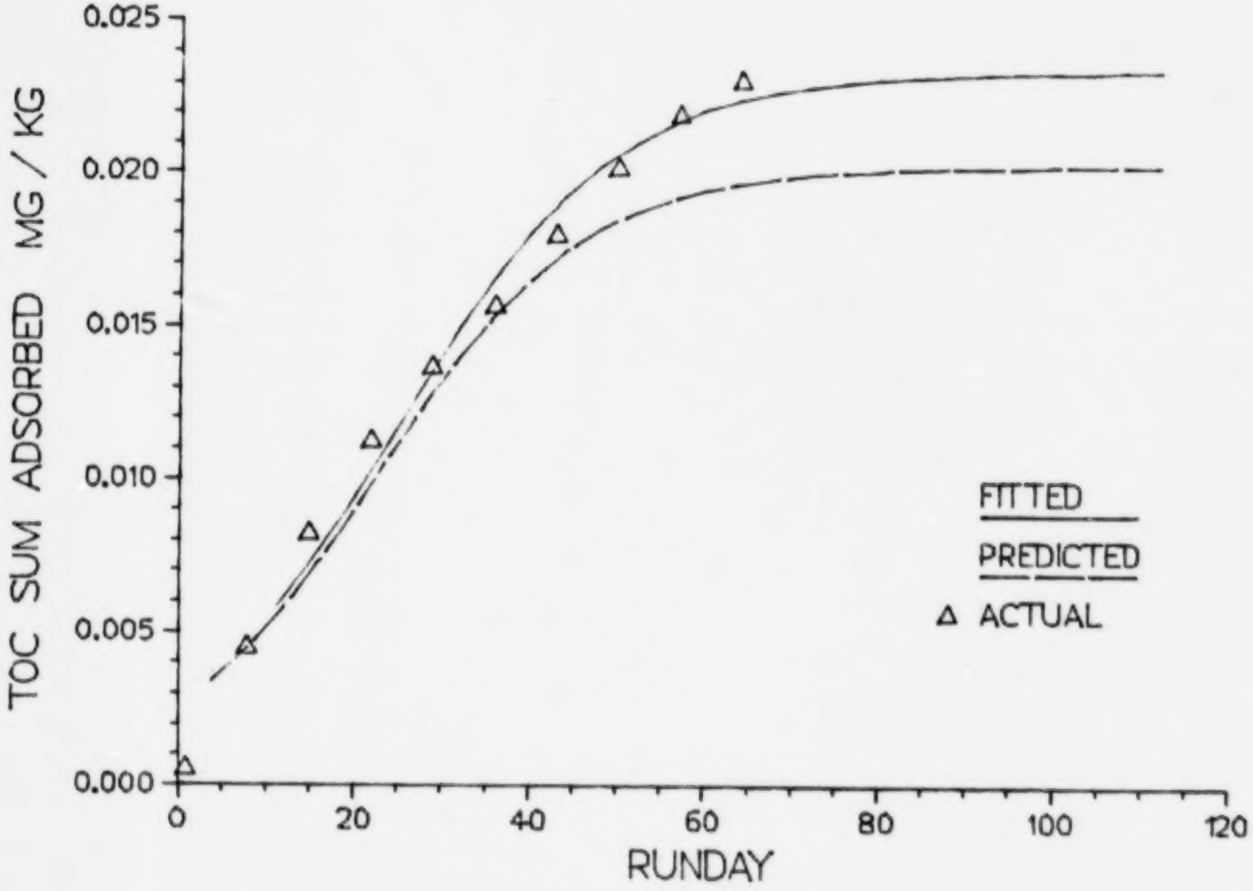

FIGURE 76. MODEL CASE STUDY 4.
LOADING CURVES FOR GAC FILTER ADSORBER, THIRD REACTIVATION – CINCINNATI, OH.

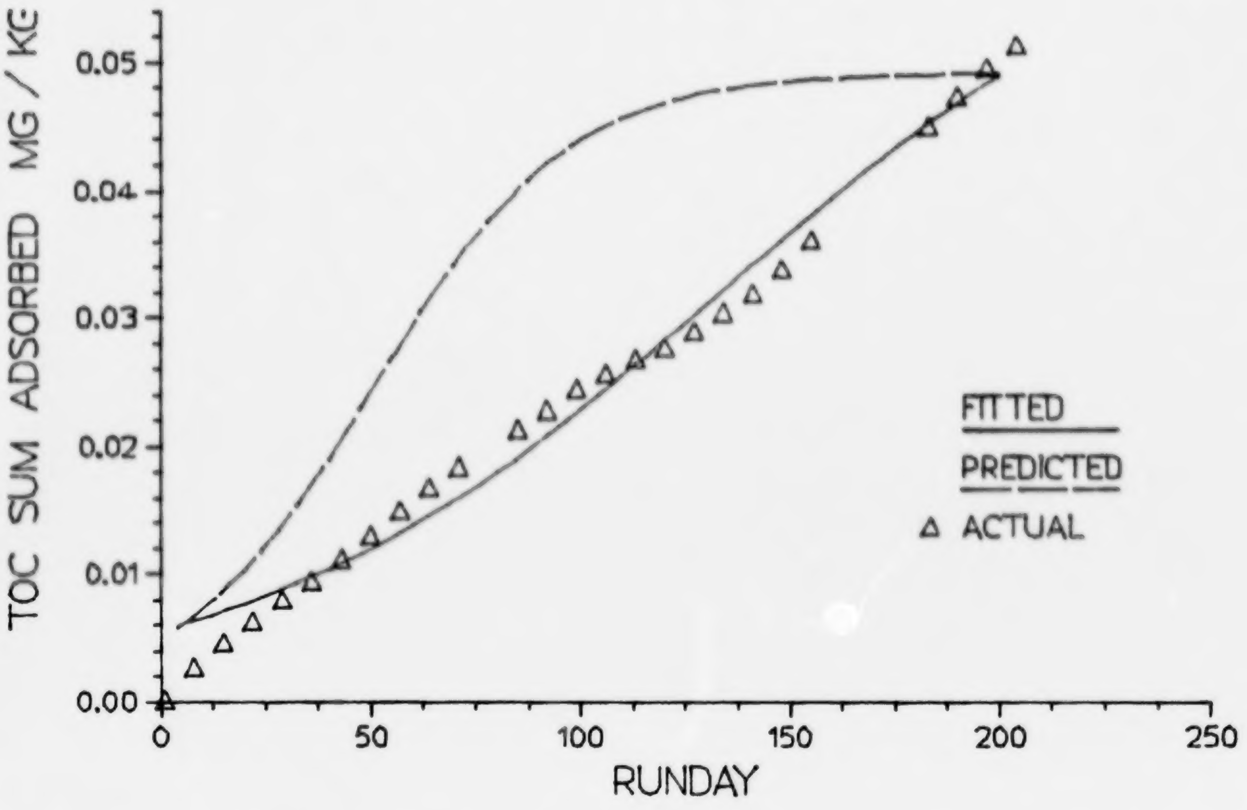

FIGURE 77. MODEL CASE STUDY 5.
LOADING CURVES FOR GAC CONTACTOR, VIRGIN GAC — CINCINNATI, OH.

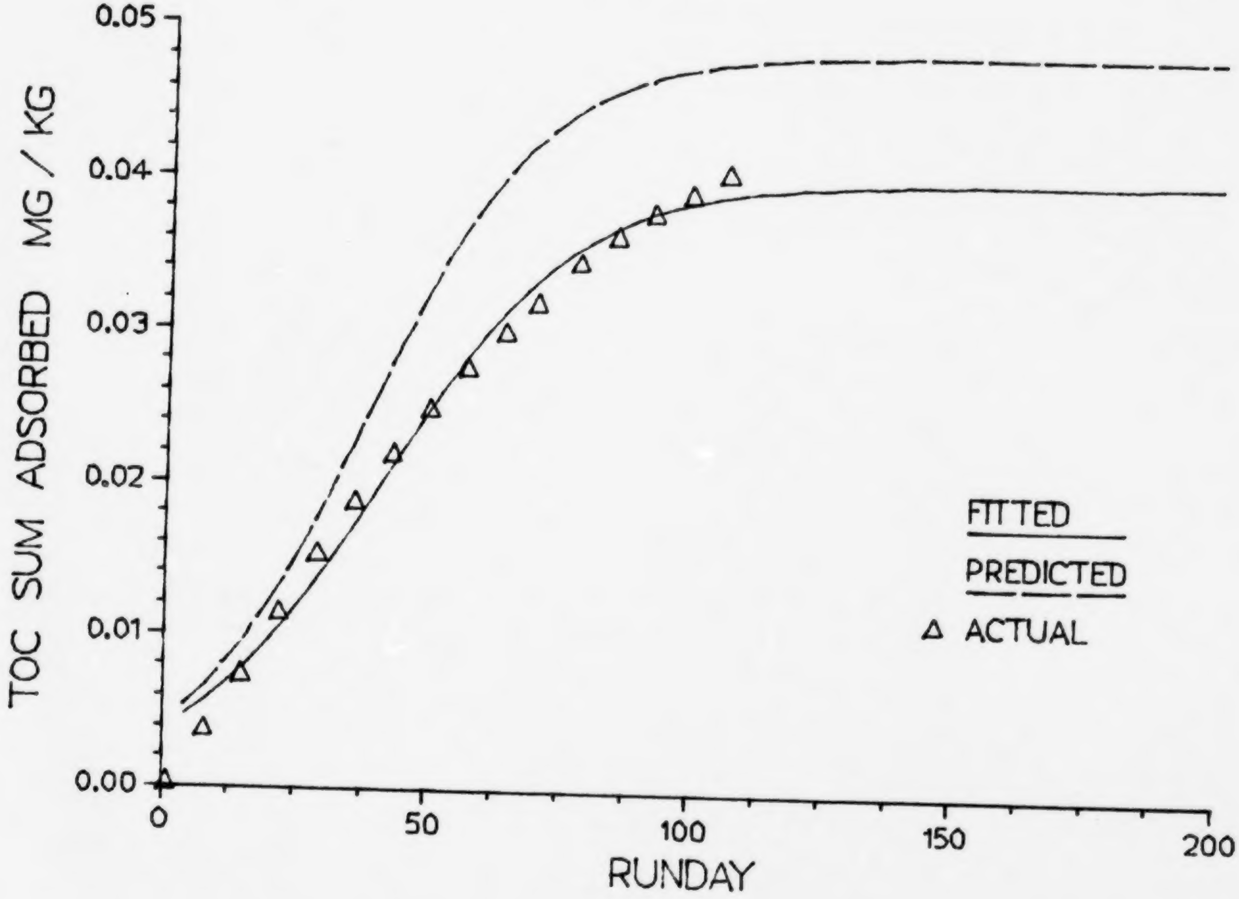

FIGURE 78. MODEL CASE STUDY 6.
LOADING CURVES FOR GAC CONTACTOR, FIRST REACTIVATION – CINCINNATI, OH.

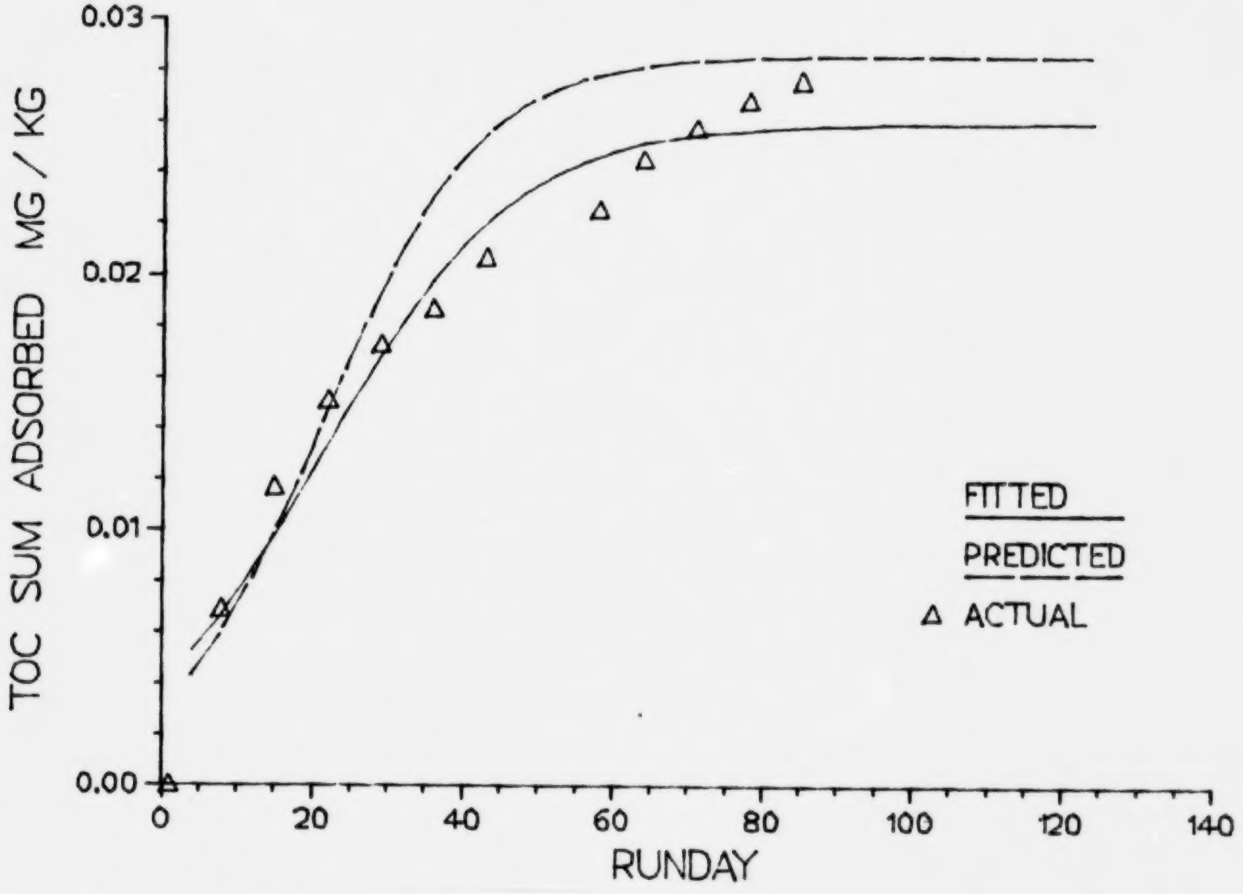

FIGURE 79. MODEL STUDY CASE 7.
LOADING CURVES FOR VIRGIN GAC CONTACTOR FOR FIRST REACTIVATION – EVANSVILLE, IN.

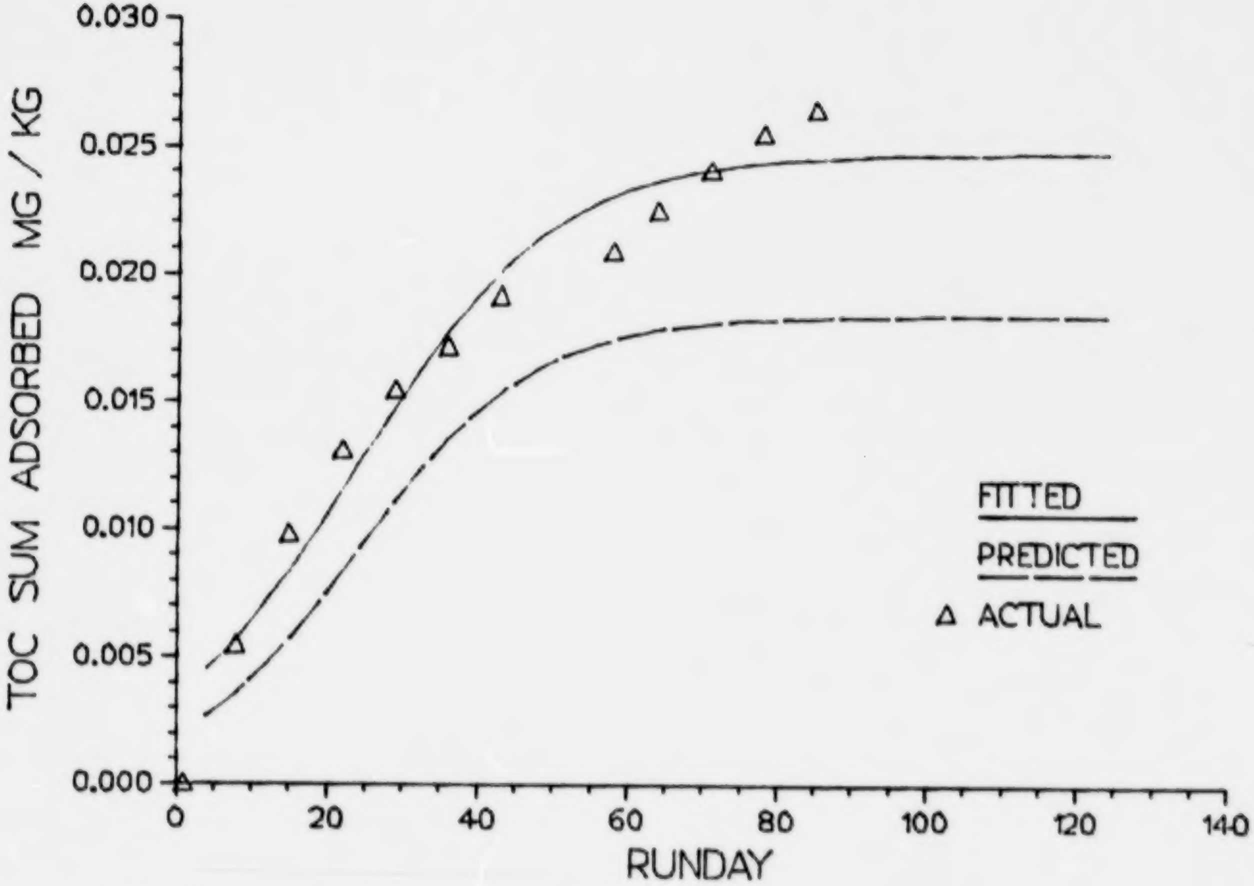

FIGURE 80. MODEL STUDY CASE 8.
LOADING CURVES FOR FIRST REACTIVATED GAC CONTACTOR
EVANSVILLE, IN.

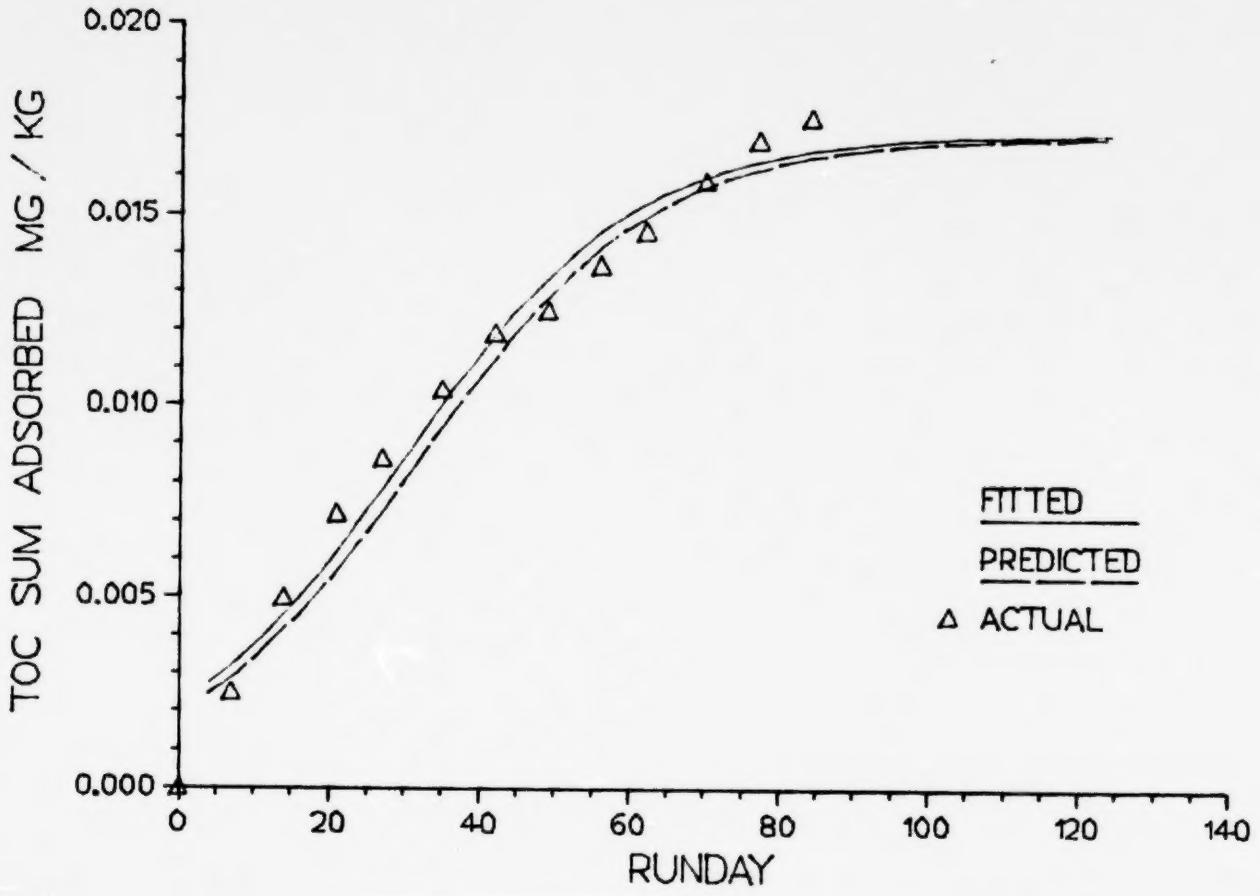

FIGURE 81. STUDY CASE 9.
LOADING CURVES FOR VIRGIN GAC CONTACTOR FOR SECOND REACTIVATION
EVANSVILLE, IN.

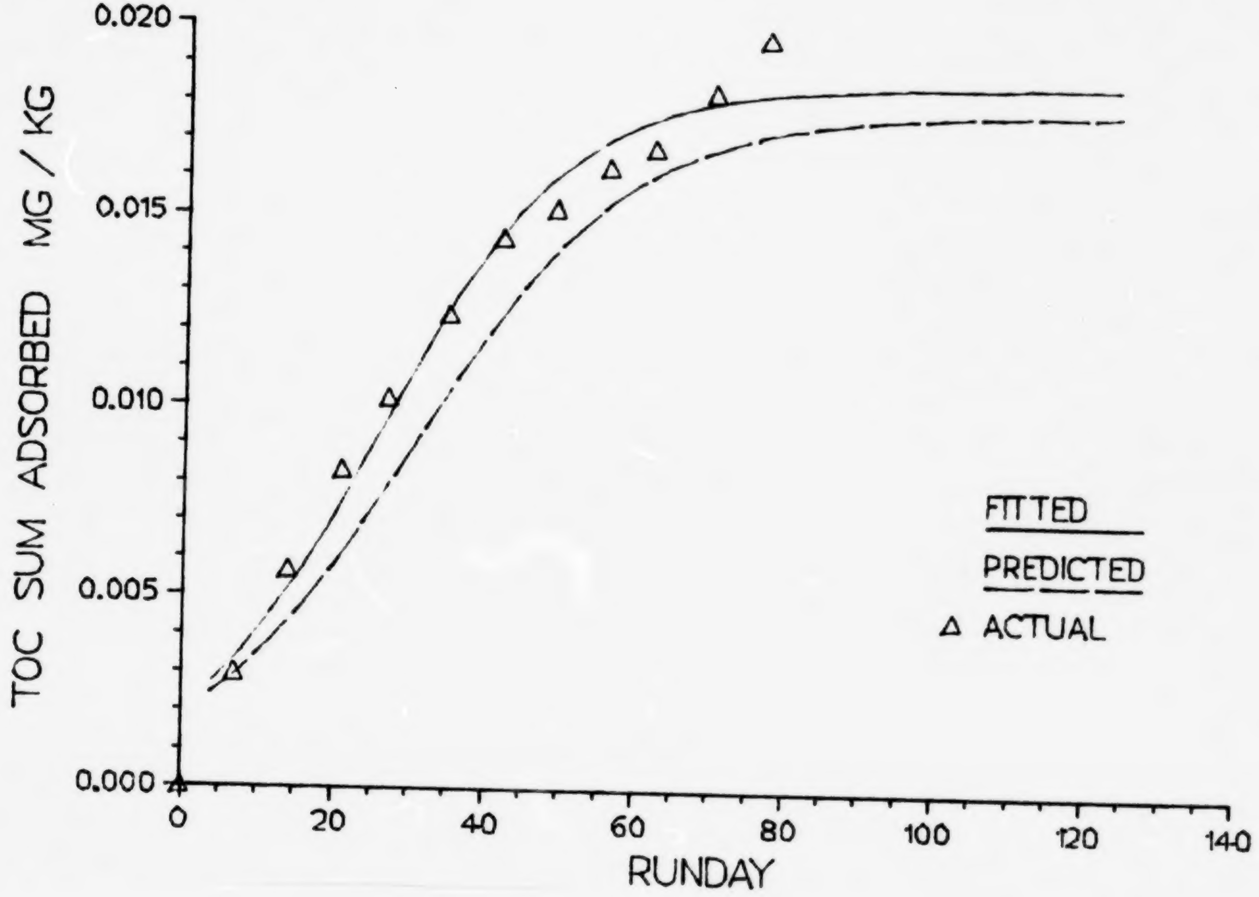

FIGURE 82. MODEL STUDY CASE 10.
LOADING CURVES FOR SECOND REACTIVATED GAC CONTACTOR – EVANSVILLE, IN.

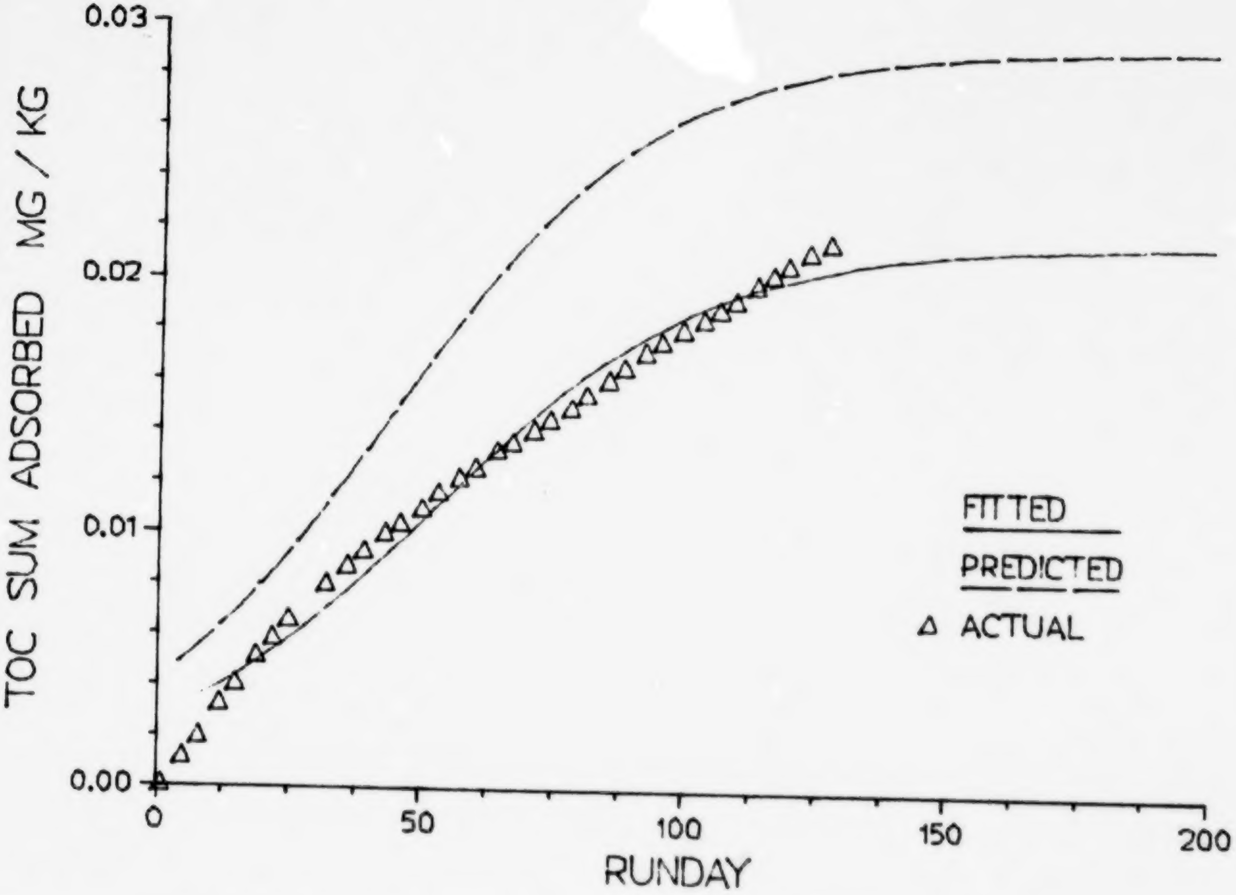

FIGURE 83. MODEL STUDY CASE 13.
LOADING CURVES FOR FIRST REACTIVATED GAC FILTER – MANCHESTER, NH.

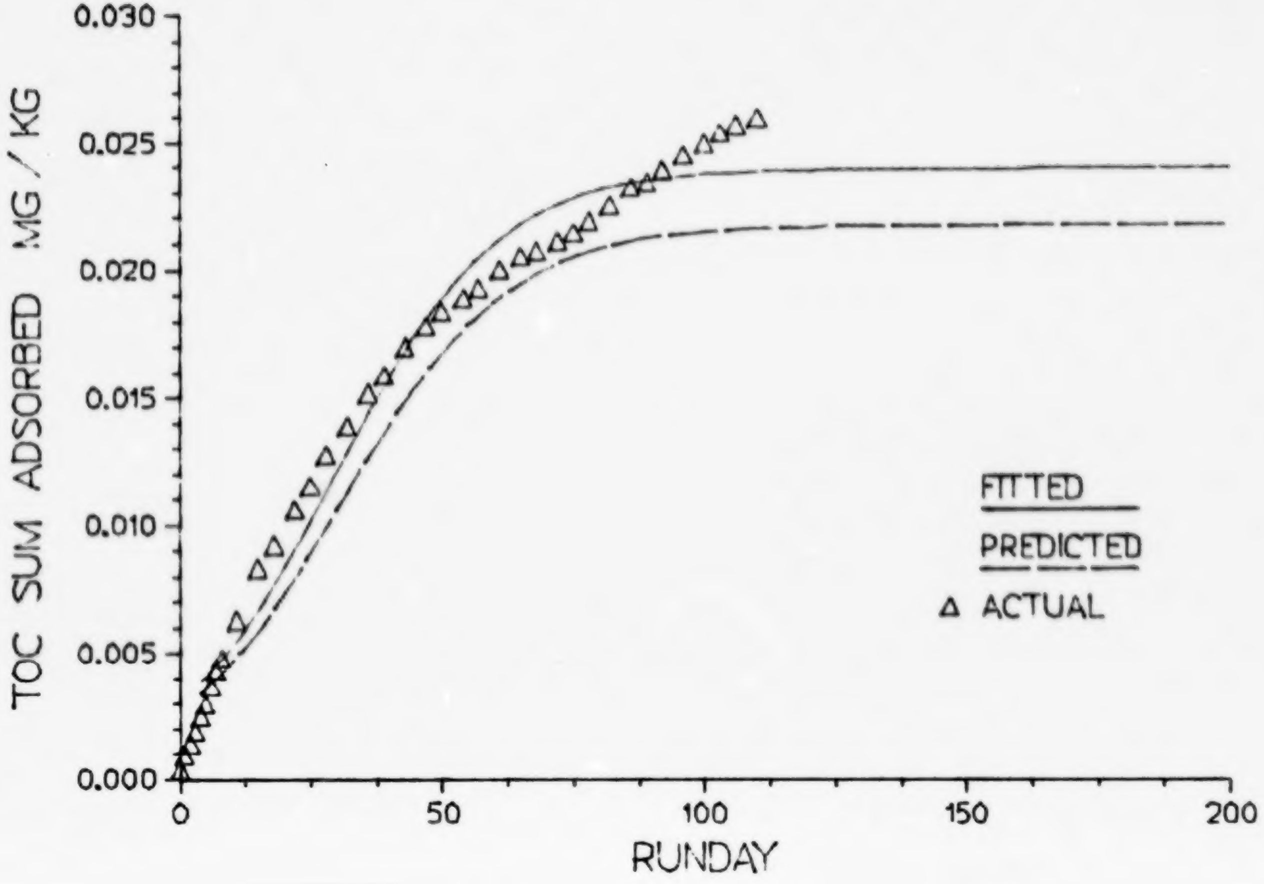

FIGURE 84. MODEL STUDY CASE 14.
LOADING CURVES FOR SECOND REACTIVATED GAC FILTER – MANCHESTER, NH.

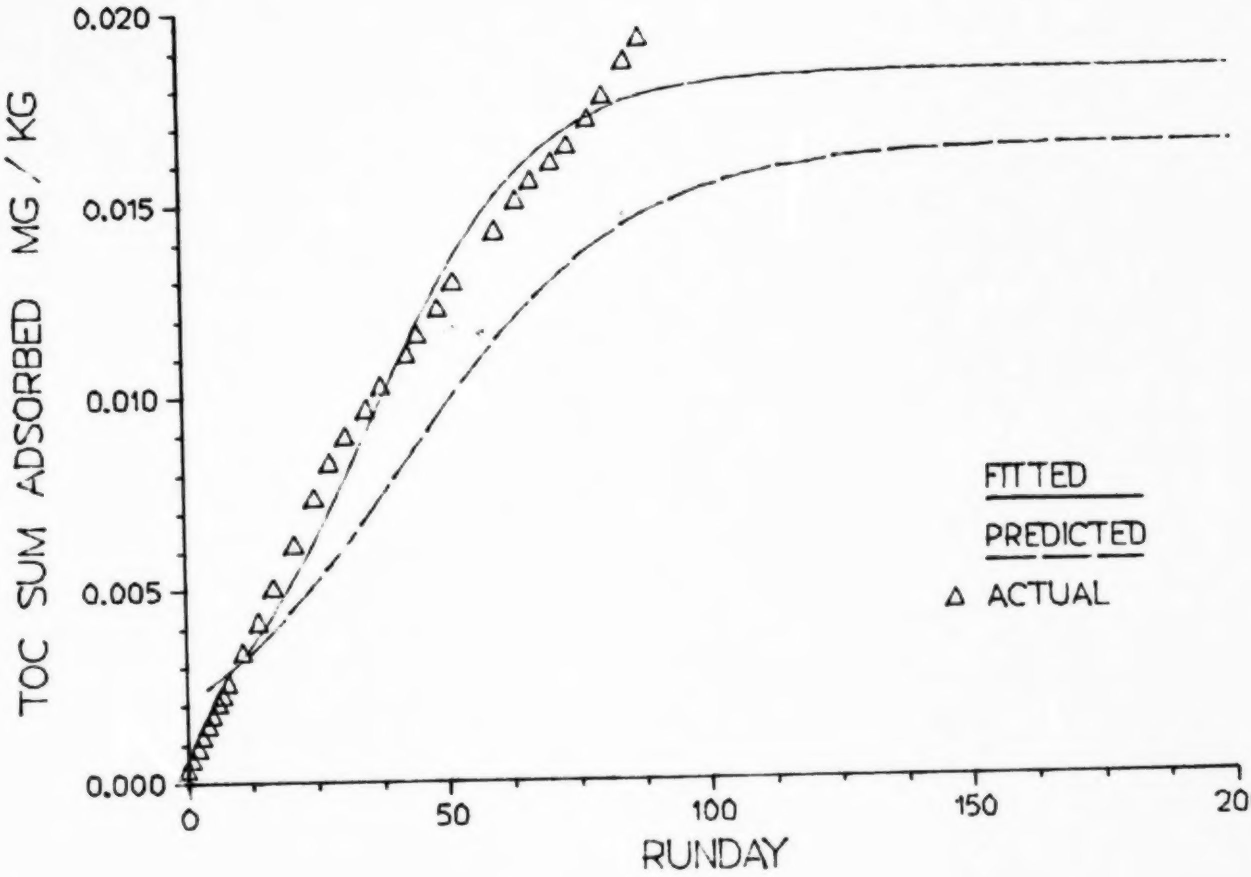

FIGURE 85. MODEL STUDY CASE 15.
LOADING CURVES FOR THIRD REACTIVATED GAC FILTER –
MANCHESTER, NH.

From these figures it is evident that the model generally provides quite reasonable estimations of the actual loading profiles. The average deviation between predicted and actual loading curves is on the order of ± 10 ug/kg for the cases studied. In addition, this methodology is expected to yield first order approximations of the TOC adsorption capacity of a given GAC sample without the use of sophisticated numerical and theoretical calculations.

Comparison of Full Scale and Pilot Scale GAC Filter Adsorber and Contactor Loading Capacities

Equation 1 was utilized successfully to fit the actual TOC loading data for seven pilot columns. Lack of physio-chemical parameter data (i.e., iodine number etc.) for the pilot study GAC samples prohibited application of the predictive capacity equations. The "fitted" capacity values from Equation 1, however, allowed empirical comparison of pilot versus full scale GAC systems operated under similar conditions. A description of the case studies is presented in the Appendix.

Tables 72 lists the best fit values for K, C, and R in Equation 1 for TOC. Figures 86 through 92 display adsorption versus runtime plots with fitted pilot and full scale data overlayed. These figures show that the pilot columns tend to over-estimate the total loading capacity of the full scale filter adsorbers by about 15% for TOC. Conversely, the pilot columns tend to underestimate the total loading capacity of the full scale contactors by about 14% for TOC. These systematic differences are probably accounted for by different EBCTs in the pilot columns versus the full scale contactors.

Summary of GAC Loading Prediction

Given iodine number, molasses number, rate of TOC applied, EBCT, mesh size, mean particle diameter and bed depth for a particular GAC sample and contactor system, reasonably accurate estimations of the TOC loading capacity in a full scale GAC system can be made. The procedure utilizes equation 1 which is an empirical first order approximation to typical cumulative loading profiles observed in actual field study data.

The modeling procedure requires a straightfoward calculation of the GAC loading based on TOC influent and effluent concentrations, total mass and volume of carbon, and flow data in conjunction with regression derived values of the three parameters, K, C and R of equation 1. The overall accuracy of the model equations given in table A-25 will no doubt improve as more physio-chemical GAC data is collected to increase the total number of model study cases. Such work is currently in progress.

TABLE 72. EQUATION 1 PARAMETER VALUES FOR TOC

CASE	PILOT SCALE	FULL SCALE
1	K = 5.846 C = 0.03917 R = 0.03373	K = 5.576 C = 0.03121 R = 0.04598
2	K = 5.906 C = 0.03240 R = 0.08946	K = 9.123 C = 0.02879 R = 0.1375
3	K = 10.37 C = 0.02196 R = 0.1216	K = 7.767 C = 0.02001 R = 0.1304
4	K = 4.935 C = 0.02952 R = 0.05279	K = 7.500 C = 0.02336 R = 0.08045
5	K = 9.731 C = 0.04989 R = 0.01993	K = 10.62 C = 0.06451 R = 0.01757
6	K = 9.438 C = 0.03676 R = 0.05718	K = 9.382 C = 0.04022 R = 0.05443
7	K = 9.773 C = 0.03039 R = 0.04265	K = 10.28 C = 0.03484 R = 0.03808

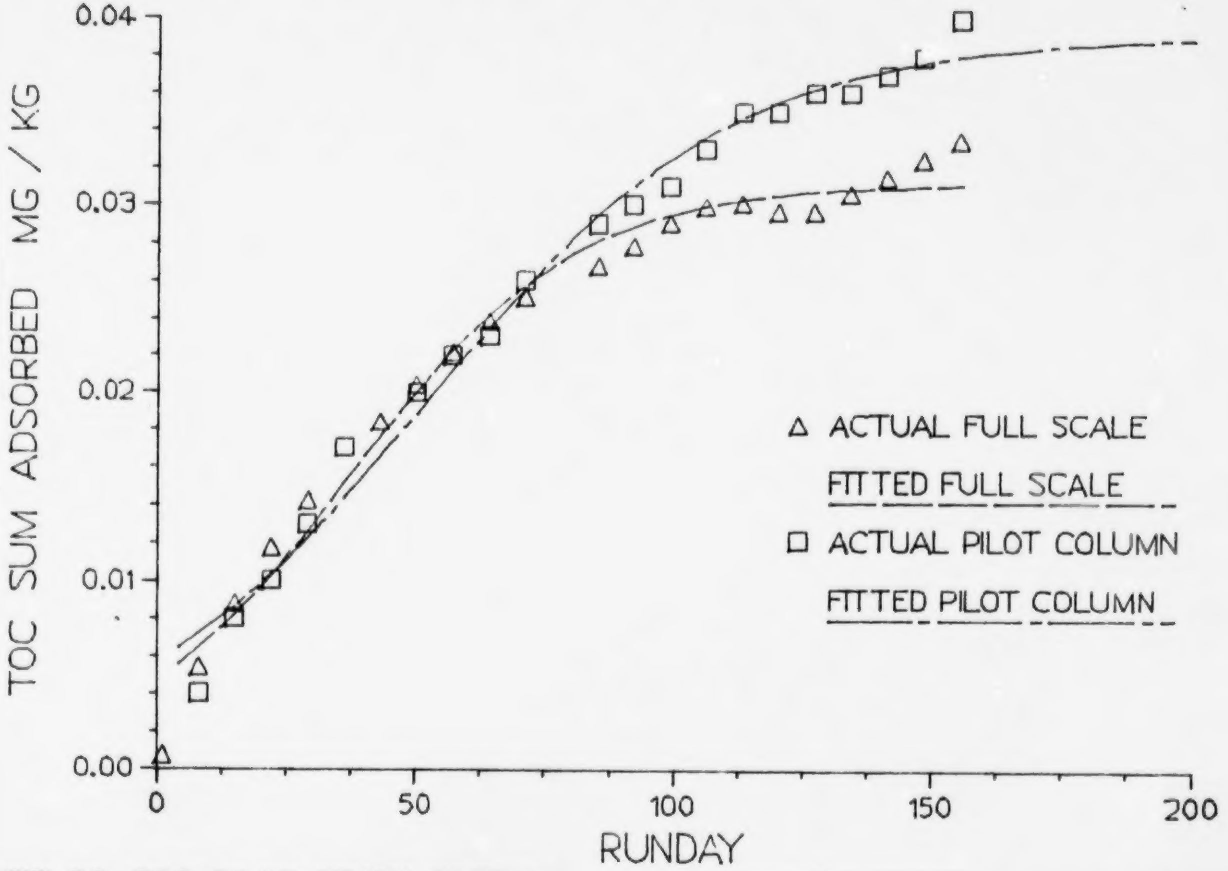

FIGURE 86. TOC PILOT STUDY CASE 1.
COMPARISON OF FILTER ADSORBER WITH PILOT COLUMN, VIRGIN GAC — CINCINNATI, OH.

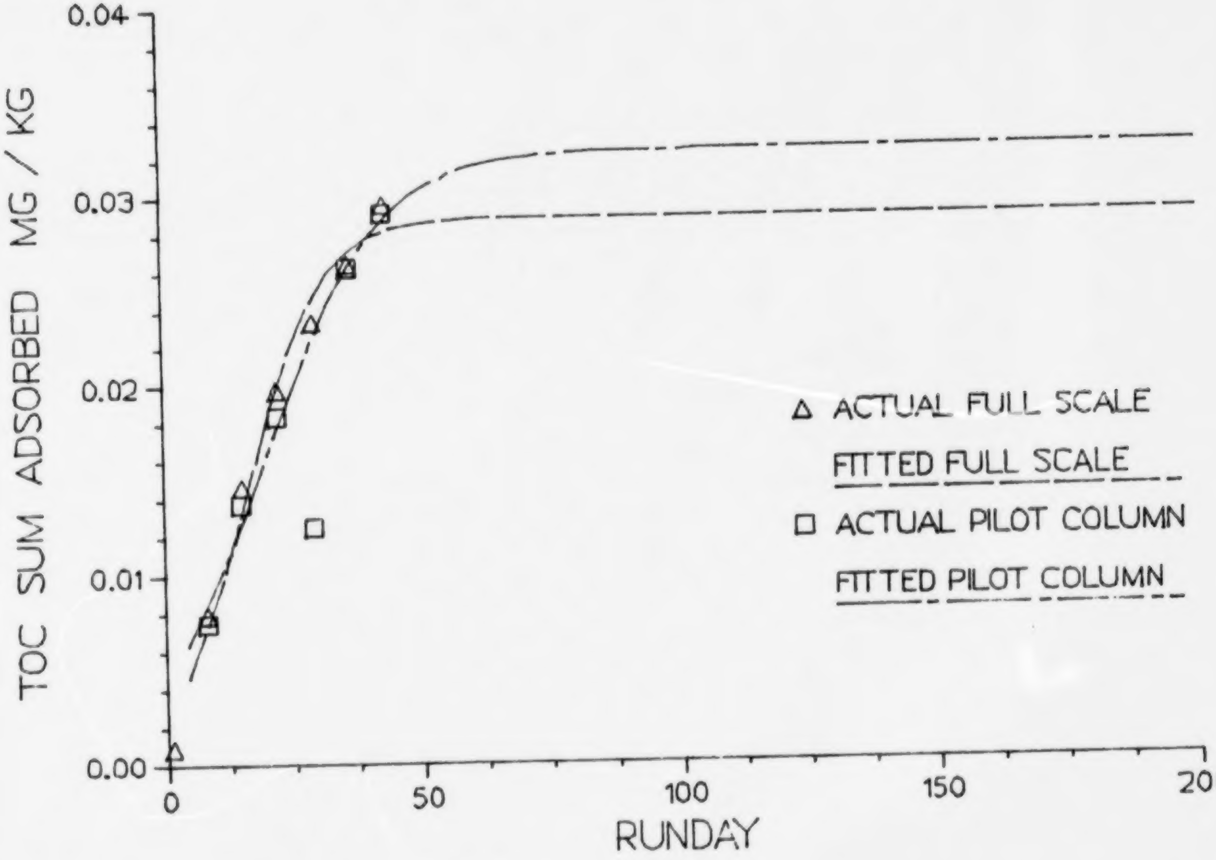

FIGURE 87. TOC PILOT STUDY CASE 2.
COMPARISON OF FILTER ADSORBER WITH PILOT COLUMN, ONCE REACTIVATED GAC – CINCINNATI, OH.

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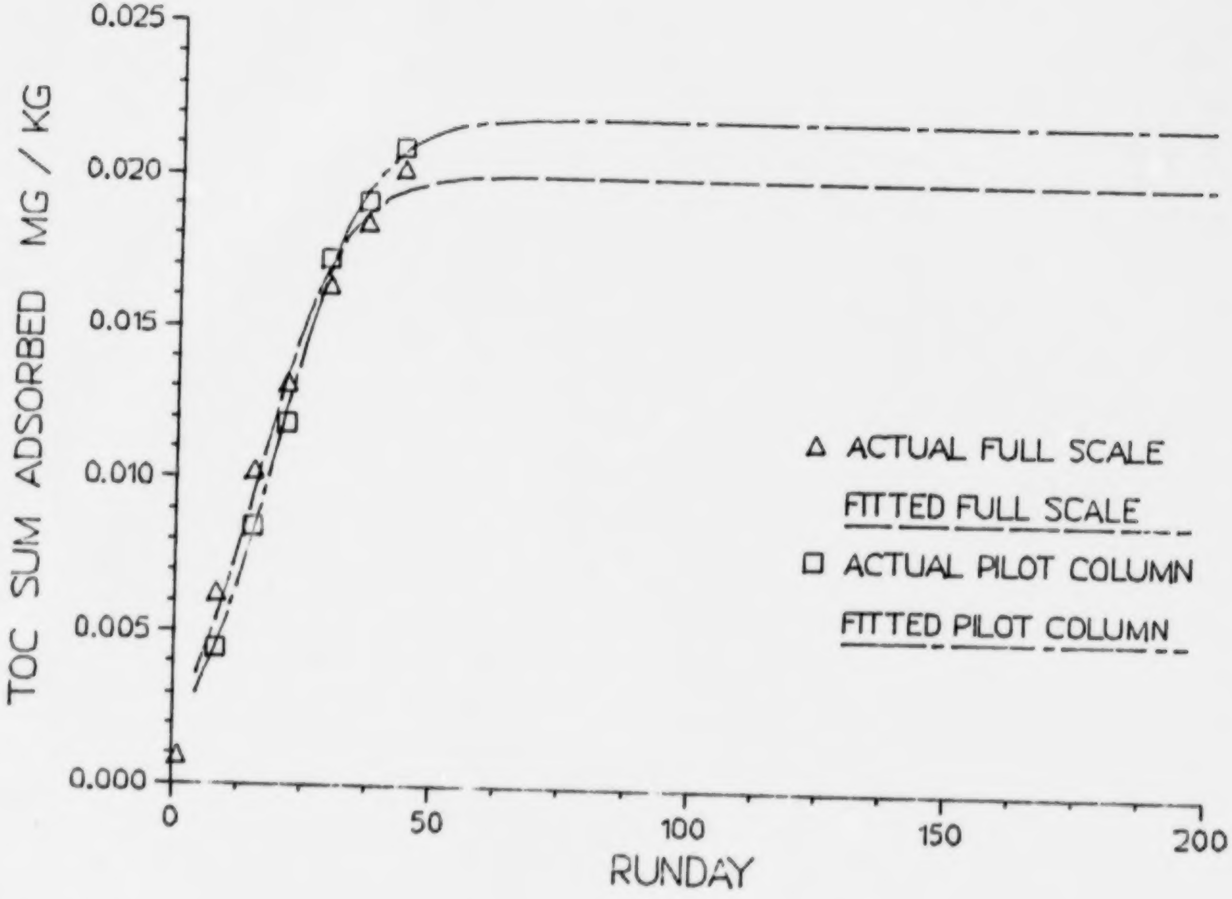

FIGURE 88. TOC PILOT STUDY CASE 3.
COMPARISON OF FILTER ADSORBER WITH PILOT COLUMN, TWICE REACTIVATED GAC – CINCINNATI, OH.

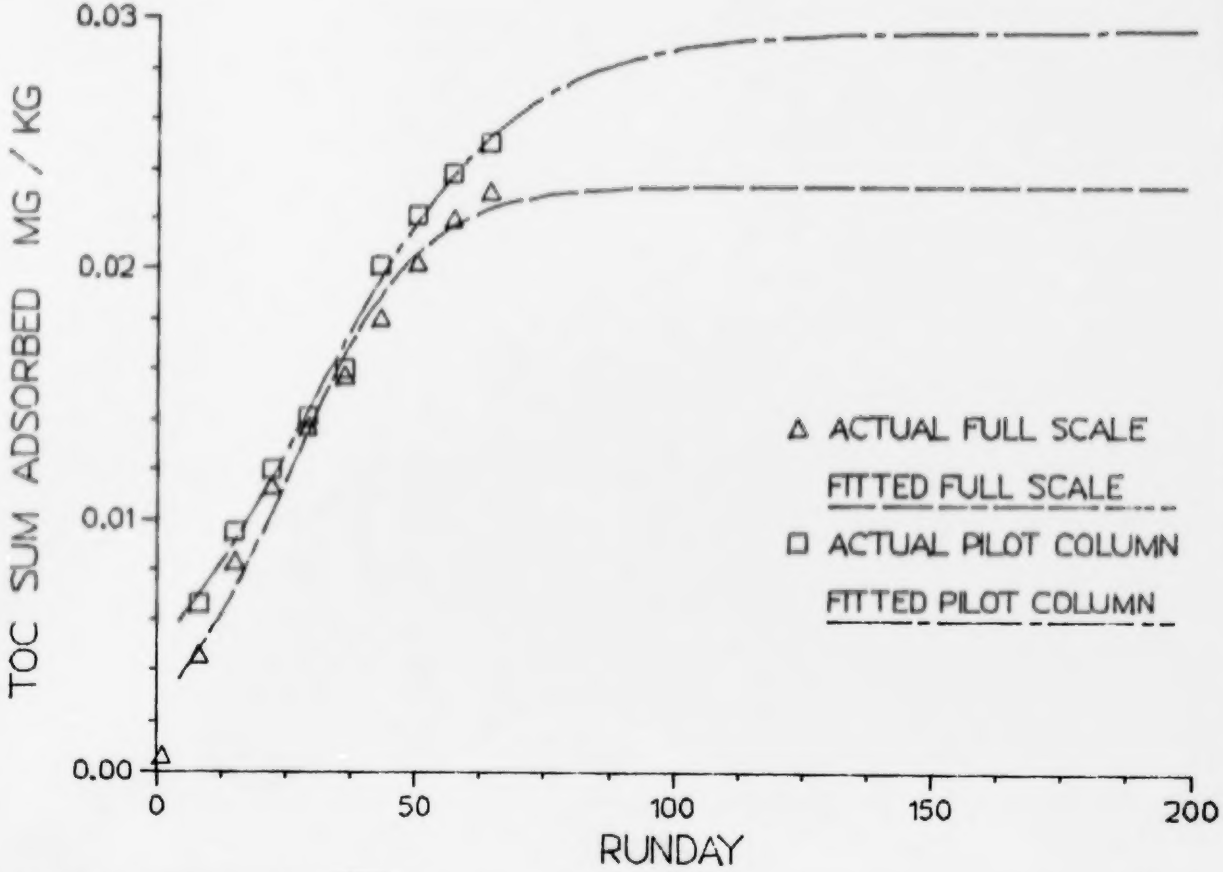

FIGURE 89. TOC PILOT STUDY CASE 4.
COMPARISON OF FILTER ADSORBER WITH PILOT COLUMN,
THRICE REACTIVATED GAC – CINCINNATI, OH.

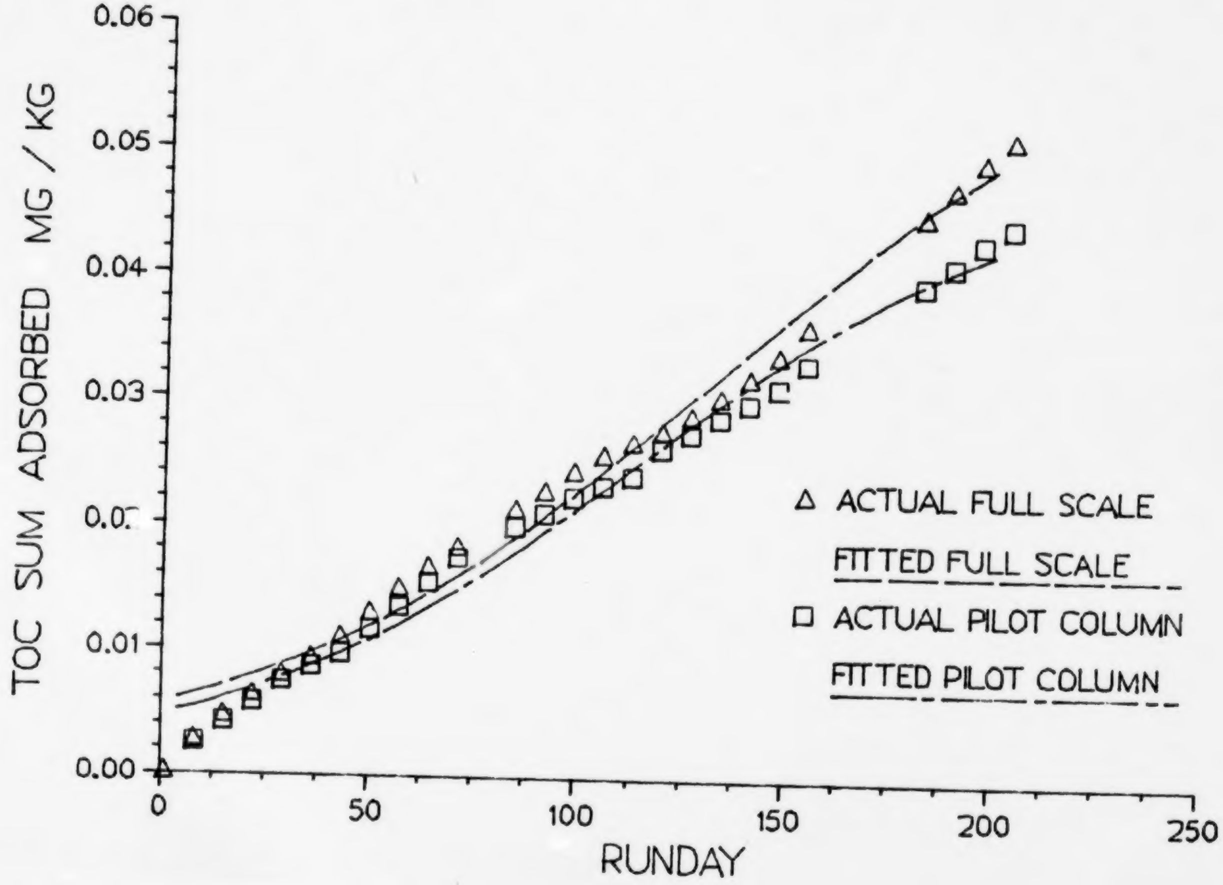

FIGURE 90. TOC PILOT STUDY CASE 5.
COMPARISON OF CONTACTOR WITH PILOT COLUMN, VIRGIN GAC — CINCINNATI, OH.

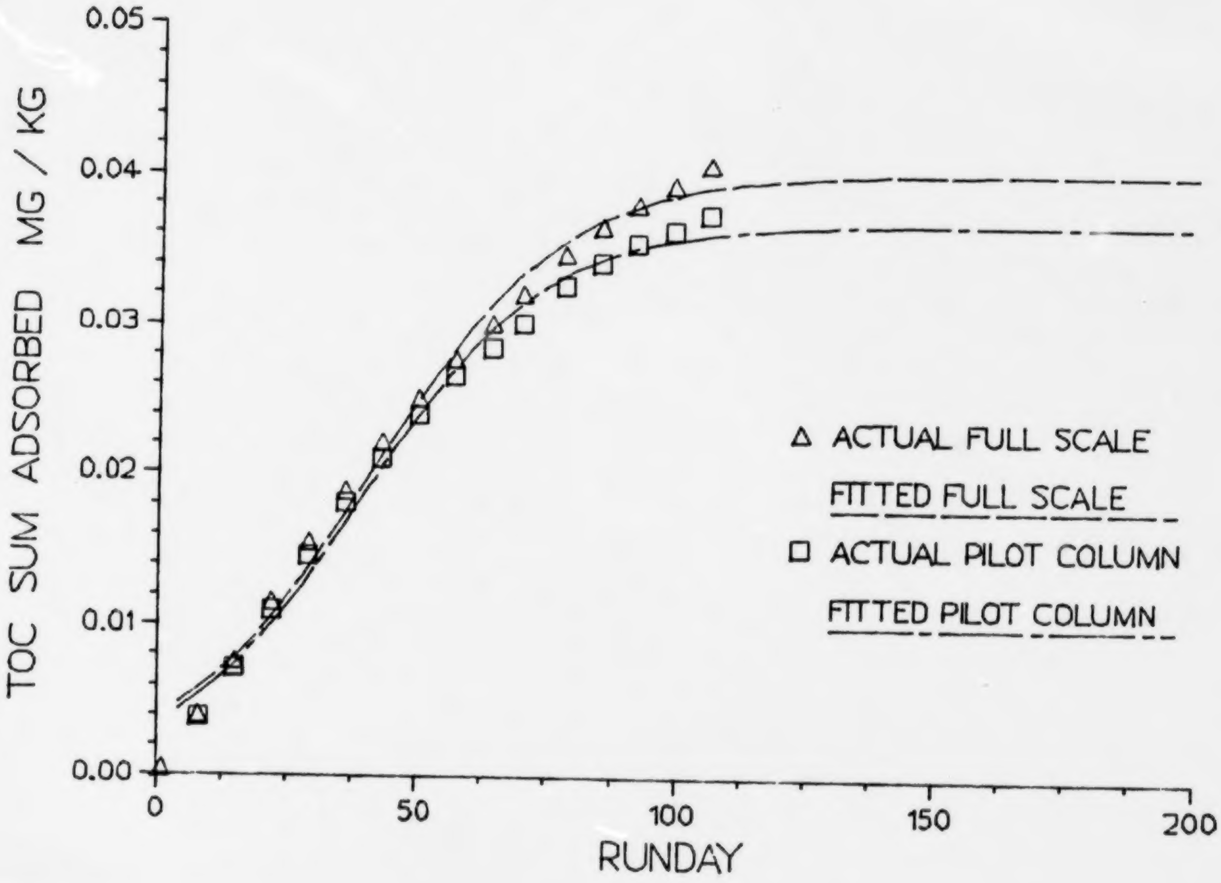

FIGURE 91. TOC PILOT STUDY CASE 6.
COMPARISON OF CONTACTOR WITH PILOT COLUMN, ONCE REACTIVATED GAC –
CINCINNATI, OH.

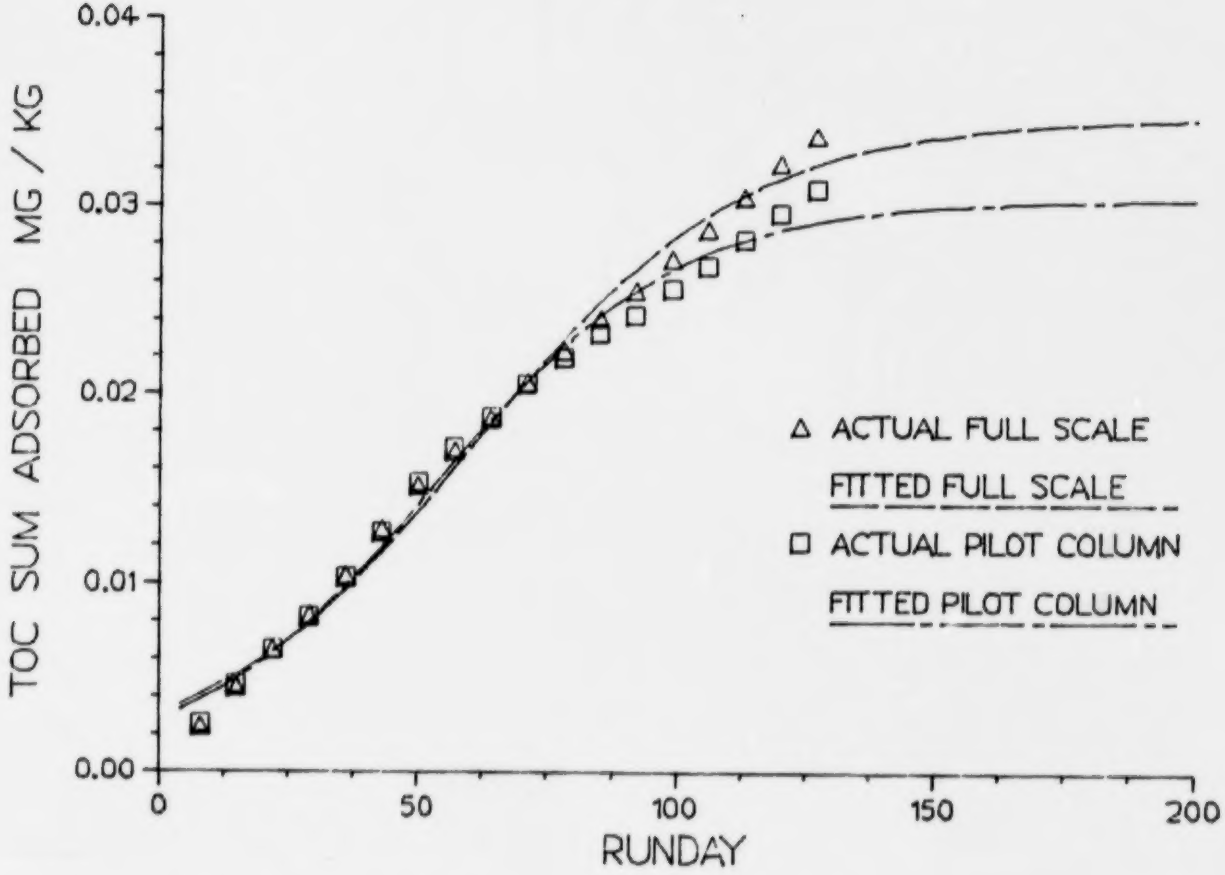

FIGURE 92. TOC PILOT STUDY CASE 7.
COMPARISON OF CONTACTOR WITH PILOT COLUMN, TWICE REACTIVATED GAC – CINCINNATI, OH.

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APPENDIX

TABLE A-1. EXPLANATION OF ON-SITE REACTIVATION COST ITEMS FOR MANCHESTER

A) Makeup Carbon. Based on an average total carbon loss of 11.5% experienced through 5 cycles of reactivation at a delivered cost to Manchester of $1.36/kg (61.50¢/lb).

B) Labor for Reactivation Operation and Maintenance. Based on a staff of 12 water treatment plant operators at an average wage of $7.32/hr. Each operator spent an average of 9.4 hours of a 42-hour workweek operating and maintaining the GAC reactivator.

C) Labor for Transport Operation and Maintenance. Based on a staff of 12 water treatment plant operators at an average wage of $7.32/hr. Each operator spent an average of 1.6 hours of a 42-hour workweek transporting GAC to and from the filter beds to the reactivator.

D) Labor for Laboratory Analysis to monitor quality control of the reactivation process. Based on a staff of 1 laboratory technician at a wage of $7.56/hr. This technician spent an average of 9.8 hours of a 35-hour workweek associated with GAC reactivation work.

E) Labor for Administration. Based on a staff of 2 engineers, chemist, secretary, purchasing agent and accountant. Each individual spent an average of 9.8 hours of a 35-hour workweek associated with GAC reactivation work.

F) Parts and Service Calls. Based on a total item cost of $49,587 for new parts, repair shop charges, and outside service calls. This work does not include Manchester Water Works labor.

G) Fuel Oil. Based on an average cost of $0.273/L ($1.035/gal) of fuel oil, and consumption of 42.4 L/hr (11.2 gals/hr) during reactivation for 6,601 BTU/kg of GAC (2,994 BTU/lb of GAC).

H) Electrical Power. Based on an average cost of 5.32¢/KWH and a consumption of 48.6 KW/hr of operation for process and building energy, or 0.205 KWH/kg of GAC (0.093/lb) .

I) Water. Based on water production cost of $.0848/m^3 ($0.321/1,000 gals) and a consumption of 44.64m^3/hr (11,792 gals/hr) of reactivator operation, or 0.189m^3/kg (22.7 gals/lb) of GAC. This includes water for both transport and reactivation. Approximately, 92% of the water is for reactivation and 8% used for transport.

J) Lab Supplies to perform reactivation process quality control analysis. Based on a total item cost of $929.

K) Depreciation. Based on the straight line depreciation calculations shown in Table 64.

TABLE A-1 (Cont'd)

L) Overhead. Based on a MWW overhead factor of 77% above labor costs that include holidays, vacations, sick leave and fringe benefits. The total overhead for the overall MWW system is 305% and includes acquisition, treatment, distribution, and support services.

TABLE A-2. MANCHESTER WATER WORKS REGIONAL REACTIVATION: CONNECTICUT WATER CO.

1. UTILITY:	Connecticut Water Co.
2. TYPE & GRADE OF GAC:	Carborundum 8 x 30 (Lignite)
3. WEIGHT OF GAC REACTIVATED:	17,070 Kgs (37,632 Lbs)
4. VOLUME OF GAC REACTIVATED:	41.8 m^3 (1,476 ft^3)
5. START AND	11:00 P.M., 11/16/81 to
STOP OF FIRST RUN:	5:00 P.M., 11/18/81
6. REACTIVATION PROCESS TIME FIRST RUN:	42 Hours
7. START AND	6:00 P.M., 11/20/81 to
STOP OF SECOND RUN:	6:00 P.M., 11/21/81
8. REACTIVATION PROCESS TIME SECOND RUN:	36 Hours
9. ONE WAY DISTANCE TO UTILITY:	277 Kilometers (172 Miles)
10. ONE WAY TRAVEL TIME:	3.5 Hours
11. VOLUMETRIC REACTIVATION LOSSES[*]	FIRST RUN: 15.4%
	SECOND RUN: 15.6%
	AVERAGE: 15.5%
12. TOTAL VOLUMETRIC LOSSES[†]	FIRST RUN: 22%
	SECOND RUN: 25%
	AVERAGE: 23.5%

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[*] Volumetric losses resulting from reactivation only.
[†] Volumetric losses resulting from reactivation and transportation.

TABLE A-3. MANCHESTER WATER WORKS REACTIVATION COSTS FOR THE CONNECTICUT WATER CO. CARBON

COST ITEM	TOTAL COST	TOTAL UNITS	UNIT RATES
A) Makeup Carbon	$ 9,816	4,011 kg (8,843 lbs)	$ 2.45/kg ($1.11/lb)
B) Labor for Reactivation	2,393	308 man-hours	7.77/hr
C) Labor for Transportation	800	103 man-hours	7.77/hr
C1) Equipment for Transportaion	2,020	554 (344 miles)	3.65/km (5.87/mile)
D) Labor for Lab	103	13 man-hours	7.91/hr
E) Labor for Administration	1,449	112 man-hours	12.94/hr
F) Parts and Service Calls	1,574	N/A	1,574.00/utility
G) Fuel Oil	1,159	3,816 L (1,008 gals)	0.304/L (1.15/gal)
H) Electrical Power	426	6,000 KWH	0.071/KWH
I) Water	873	5,453 m^3 (1,440,594 gals)	0.160/m^3 (0.606/1,000 gals)
J) Lab Supplies	100	N/A	100.00 utility
K) Depreciation	564	78 hours	7.23/hr of reactivation
L) Overhead	3,654	N/A	77% of labor
TOTAL	$ 24,931		

N/A = Not Applicable

NOTE: November 16, 1981 to November 21, 1981
Based on reactivation of 17,070 kgs (37,632 lbs) of GAC

TABLE A-4. EXPLANATION OF MANCHESTER WATER WORKS REACTIVATION COST ITEMS FOR THE CONNECTICUT WATER COMPANY

A) Makeup Carbon. Based on a total volumetric carbon loss of 23.5% experienced through one cycle of reactivation at a delivered cost to Connecticut of \$2.45/kg (\$1.11/lb).

B) Labor for Reactivation Operation and Maintenance. Based on a staff of 12 water treatment plant operators at an average wage of \$7.77/hr. Approximately 308 man-hours of labor time was used to reactivate the Connecticut GAC.

C) Labor for Transportation. Based on 2 water treatment plant operators at an average wage of \$7.77/hr used to load and off-load the GAC at the Manchester reactivator, and to assist loading and off-loading the GAC at the Connecticut water treatment facility. Approximately 103 man-hours of labor was used to transport the GAC.

C1) Equipment for Transportation. Based on a truck rental of \$30.00/hr for the tractor and driver with a use of 46.25 hours, and \$100.00/day for the trailer with a use of 6.3 days.

D) Labor for Laboratory Analysis to monitor quality control of the reactivation process. Based on a staff of one laboratory technician at a wage of \$7.91/hr. Approximately 13 man-hours of labor time was used to perform the analysis.

E) Labor for Administration. Based on a staff of 2 engineers, chemist, secretary, purchasing agent and accountant. Approximately 112 man-hours of administrative labor was used during the Connecticut work.

F) Parts and Service Calls. Based on a total item cost of \$4,722 divided equally by the 3 utilities that participated in the program for new parts, repair shop charges, and outside service calls. This item does not include MWW labor.

G) Fuel Oil. Based on an average of \$0.304/liter (\$1.15/gallon) of fuel oil and consumption of 42.4 liters/hr (11.2 gallons/hr) of reactivation or 6,959 Joules/gram (2,994 BTU/lb) of carbon.

H) Electrical Power. Based on an average cost of 7.10¢/KWH and a consumption of 48.6 KW/hr of operation for building and process energy, or 0.205 KWH/kg (0.093 KWH/lb) of GAC.

I) Water. Based on a water production cost of \$0.160/m^3 (\$0.606/1,000 gals) and a consumption of 44.64 m^3/hr (11,792 gals/hr) of reactivator operation, or 0.189 m^3/kg (22.7 gals/lb) of GAC. Approximately 92% of the water was used for reactivation and 8% used for on-site transport.

TABLE A-4 (Cont'd)

J) Lab Supplies. Based on a total item cost of $300., divided equally by the 3 utilities that participated in the program for supplies to perform reactivation process quality control analysis.

K) Depreciation. Based on the straight line depreciation calculations shown in Table 7.

L) Overhead. Based on a MWW overhead factor of 77% above labor costs that includes holidays, sick leave and fringe benefits. The total overhead for the overall MWW system is 305% and includes acquistion, treatment, distribution, and support services.

TABLE A-5. MANCHESTER WATER WORKS REACTIVATION UNIT COSTS FOR THE CONNECTICUT WATER CO. CARBON

	Cost Item	Cost Per Kg	(Cost Per Lb)
A)	Makeup Carbon	57.50¢	(26.08¢)
B)	Labor for Reactivation	14.02	(6.36)
C)	Labor for Transportation	4.67	(2.12)
C1)	Equipment for Transportation	11.84	(5.37)
D)	Labor for Lab	0.62	(0.28)
E)	Labor for Administration	8.49	(3.85)
F)	Parts and Service Calls	9.22	(4.18)
G)	Fuel Oil	6.79	(3.08)
H)	Electrical Power	2.49	(1.13)
I)	Water	5.11	(2.32)
J)	Lab Supplies	0.60	(0.27)
K)	Depreciation	3.31	(1.50)
L)	Overhead	21.38	(9.70)
	TOTAL COST	146.04¢	(66.24¢)

November 16, 1981 to November 21, 1981
Based on Reactivation of 17,070 kgs (37,632 lbs) of GAC

TABLE A-6. MANCHESTER WATER WORKS REGIONAL REACTIVATION: DANVERS, MASSACHUSETTS

1. UTILITY:	Danvers, Massachusetts
2. TYPE & GRADE OF GAC:	Calgon Filtrasorb 300
	Coal Base 8 x 30
3. WEIGHT OF GAC REACTIVATED:	16,601 Kgs (36,000 Lbs)
4. VOLUME OF GAC REACTIVATED:	45.55m^3 (1,538 ft^3)
5. START AND	2:00 P.M., 12/01/81 to
STOP OF FIRST RUN:	7:00 P.M., 12/03/81
6. REACTIVATION PROCESS TIME FIRST RUN:	41 Hours
7. START AND	4:45 P.M., 12/04/81 to
STOP OF SECOND RUN:	3:15 P.M., 12/05/81
8. REACTIVATION PROCESS TIME SECOND RUN:	34.5 Hours
9. ONE WAY DISTANCE TO UTILITY:	66 Kilometers (41 Miles)
10. ONE WAY TRAVEL TIME:	1 Hours
11. VOLUMETRIC REACTIVATION LOSSES*	FIRST RUN: 7.7%
	SECOND RUN: 11.1%
	AVERAGE: 9.4%
12. TOTAL VOLUMETRIC LOSSES†	FIRST RUN: 13.0%
	SECOND RUN: 9.8%
	AVERAGE: 11.4%

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*Volumetric losses resulting from reactivation only.

†Volumetric losses resulting from reactivation and transportation.

TABLE A-7. MANCHESTER WATER WORKS REACTIVATION COSTS FOR THE DANVERS, MASSACHUSETTS CARBON

COST ITEM	TOTAL COST	TOTAL UNITS	UNIT RATES
A) Makeup Carbon	$ 3,058	1,892 kg (4,172 lbs)	$ 1.62/kg ($0.733/lb)
B) Labor for Reactivation	1,447	186 man-hours	7.77/hr
C) Labor for Transportation	485	62.4 man-hours	7.77/hr
C1) Equipment for Transportaion	1,518	264 km (164 miles)	5.75/km (9.26/mile)
D) Labor for Lab	103	13 man-hours	7.91/hr
E) Labor for Administration	651	50.3 man-hours	12.94/hr
F) Parts and Service Calls	1,574	N/A	1,574.00/utility
G) Fuel Oil	1,127	3,710 L (980 gals)	0.304/L (1.15/gal)
H) Electrical Power	497	7,000 KWH	0.071/KWH
I) Water	551	3,442 m^3 (909,241 gals)	0.160/m^3 (0.606/1,000 gals)
J) Lab Supplies	100	N/A	100.00/utility
K) Depreciation	546	75.5 hours	7.23/hr of reactivation
L) Overhead	2,068	N/A	77% of labor
TOTAL	$ 13,725		

N/A = Not Applicable

NOTE: December 1, 1981 to December 5, 1981
Based on reactivation of 16,601 kgs (36,600 lbs) of GAC

TABLE A-8. EXPLANATION OF MANCHESTER WATER WORKS REACTIVATION COST ITEMS FOR DANVERS, MASSACHUSETTS

A) Makeup Carbon. Based on a total volumetric carbon loss of 11.4% experienced through one cycle of reactivation at a delivered cost to Danvers of \$1.62/kg (\$0.7329 lb).

B) Labor for Reactivation Operation and Maintenance. Based on a staff of 12 water treatment plant operators at an average wage of \$7.77/hr. Approximately 186 man-hours of labor time was used to reactivate the Danvers GAC.

C) Labor for Transportation. Based on 2 water treatment plant operators at an average wage of \$7.77/hr used to load and off-load the GAC at the Manchester reactivator, and to assist loading and off-loading the GAC at the Danvers water treatment facility. Approximately 62.4 man-hours of labor were used to transport the GAC.

C1) Equipment for Transportation. Based on a truck rental of \$30.00/hr for the tractor and driver with a use of 29.5 hours, and \$100.00/day for the trailer with a use of 6.3 days.

D) Labor for Laboratory Analysis to monitor quality control of the reactivation process. Based on a staff of one laboratory technician at a wage of \$7.91/hr. Approximately 13 man-hours of labor time were used to perform the analysis.

E) Labor for Administration. Based on a staff of 2 engineers, chemist, secretary, purchasing agent and accountant. Approximately 50 manhours of administrative labor were used during the Danvers work.

F) Parts and Service Calls. Based on a total item cost of \$4,722 divided equally by the 3 utilities that participated in the program for new parts, repair shop charges, and outside service calls. This item does not include MWW labor.

G) Fuel Oil. Based on an average of \$0.304/liter (\$1.15/gallon) of fuel oil and consumption of 42.4 liters/hr (11.2 gallons/hr) of reactivation or 6,959 Joules/gram (2,994 BTU/lb) of carbon.

H) Electrical Power. Based on an average cost of 7.10¢/KWH and a consumption of 48.6 KW/hr of operation for building and process energy, or 0.205 KWH/kg (0.093 KWH/lb) of GAC.

I) Water. Based on a water production cost of \$0.160/m^3 (\$0.606/1,000 gals) and a consumption of 44.64 m^3/hr (11,792 gals/hr) of reactivator operation, or 0.189 m^3/kg (22.7 gals/lb) of GAC. Approximately 92% of the water was used for reactivation and 8% used for on-site transport.

TABLE A-8 (Cont'd)

J) Lab Supplies. Based on a total item cost of $300., divided equally by the 3 utilities that participated in the program for supplies to perform reactivation process quality control analysis.

K) Depreciation. Based on the straight line depreciation calculations shown in Table 7.

L) Overhead. Based on a MWW overhead factor of 77% above labor costs that includes holidays, sick leave and fringe benefits. The total overhead for the overall MWW system is 305% and includes acquistion, treatment, distribution, and support services.

TABLE A-9. MANCHESTER WATER WORKS REACTIVATION UNIT COSTS FOR THE DANVERS, MASSACHUSETTS CARBON

	Cost Item	Cost Per Kg	(Cost Per Lb)
A)	Makeup Carbon	18.43¢	(8.36¢)
B)	Labor for Reactivation	8.71	(3.95)
C)	Labor for Transportation	2.93	(1.33)
C1)	Equipment for Transportation	9.13	(4.14)
D)	Labor for Lab	0.62	(0.28)
E)	Labor for Administration	3.92	(1.78)
F)	Parts and Service Calls	9.48	(4.30)
G)	Fuel Oil	6.79	(3.08)
H)	Electrical Power	3.00	(1.36)
I)	Water	3.33	(1.51)
J)	Lab Supplies	0.60	(0.27)
K)	Depreciation	3.28	(1.49)
L)	Overhead	12.46	(5.65)
	TOTAL COST	82.68¢	(37.50¢)

NOTE: December 6, 1981 to December 5, 1981
Based on Reactivation of 16,601 kgs (36,600 lbs) of GAC

TABLE A-10. MANCHESTER WATER WORKS REGIONAL REACTIVATION: LOWELL, MASSACHUSETTS

1. UTILITY:	Lowell, Massachusetts	
2. TYPE & GRADE OF GAC:	Westvaco WVW 8 x 30	
	Coal Base	
3. WEIGHT OF GAC REACTIVATED:	19,125 Kgs (42,163 Lbs)	
4. VOLUME OF GAC REACTIVATED:	33.1 m^3 (1,170 ft^3)	
5. START AND	4:00 P.M., 12/09/81 to	
STOP OF FIRST RUN:	8:00 P.M., 12/11/81	
6. REACTIVATION PROCESS TIME FIRST RUN:	40 Hours	
7. START AND	3:00 A.M., 12/15/81 to	
STOP OF SECOND RUN:	6:15 P.M., 12/16/81	
8. REACTIVATION PROCESS TIME SECOND RUN:	27.15 Hours	
9. ONE WAY DISTANCE TO UTILITY:	53.1 Kilometers (33 Miles)	
10. ONE WAY TRAVEL TIME:	45 Minutes	
11. VOLUMETRIC REACTIVATION LOSSES*	FIRST RUN:	12.5%
	SECOND RUN:	15.3%
	AVERAGE:	13.9%
12. TOTAL VOLUMETRIC LOSSES†	FIRST RUN:	14.0%
	SECOND RUN:	16.6%
	AVERAGE:	15.3%

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*Volumetric losses resulting from reactivation only.

†Volumetric losses resulting from reactivation and transportation.

TABLE A-11. MANCHESTER WATER WORKS REACTIVATION COSTS FOR THE LOWELL, MASSACHUSETTS CARBON

COST ITEM	TOTAL COST	TOTAL UNITS	UNIT RATES
A) Makeup Carbon	$ 7,354	2,926 kg (6,451 lbs)	$ 2.51/kg ($1.14/1b)
B) Labor for Reactivation	19,587	252 man-hours	7.77/hr
C) Labor for Transportation	543	69.9 man-hours	7.77/hr
C1) Equipment for Transportaion	1,308	106.2 km (66 miles)	12.32/km (19.82/mile)
D) Labor for Lab	103	13 man-hours	7.91/hr
E) Labor for Administration	833	64.4 man-hours	12.94/hr
F) Parts and Service Calls	1,574	N/A	1,574.00/utility
G) Fuel Oil	1,021	3,361 L (888 gals)	0.304/L (1.15/gal)
H) Electrical Power	476	6,704 KWH	0.071/KWH
I) Water	551	3,442 m^3 (909,241 gals)	0.160/m^3 (0.606/1,000 gals)
J) Lab Supplies	100	N/A	100.00/utility
K) Depreciation	486	67.25 hours	7.23/hr of reactivation
L) Overhead	2,646	N/A	77% of labor
TOTAL	$ 18,953		

N/A = Not Applicable

NOTE: December 9, 1981 to December 16, 1981
Based on reactivation of 19,125 kgs (42,163 lbs) of GAC

TABLE A-12. EXPLANATION OF MANCHESTER WATER WORKS REACTIVATION COST ITEMS FOR LOWELL, MASSACHUSETTS

A) Makeup Carbon. Based on a total volumetric carbon loss of 15.3% experienced through one cycle of reactivation at a delivered cost to Lowell of \$2.51/kg (\$1.14/lb).

B) Labor for Reactivation Operation and Maintenance. Based on a staff of 12 water treatment plant operators at an average wage of \$7.77/hr. Approximately 252 man-hours of labor time were used to reactivate the Lowell GAC.

C) Labor for Transportation. Based on 2 water treatment plant operators at an average wage of \$7.77/hr used to load and off-load the GAC at the Manchester reactivator, and to assist loading and off-loading the GAC at the Lowell water treatment facility. Approximately 69.9 man-hours of labor were used to transport the GAC.

C1) Equipment for Transportation. Based on a truck rental of \$30.00/hr for the tractor and driver with a use of 22.5 hours, and \$100.00/day for the trailer with a use of 6.3 days.

D) Labor for Laboratory Analysis to monitor quality control of the reactivation process. Based on a staff of one laboratory technician at a wage of \$7.91/hr. Approximately 13 man-hours of labor time was used to perform the analysis.

E) Labor for Administration. Based on a staff of 2 engineers, chemist, secretary, purchasing agent and accountant. Approximately 64 manhours of administrative labor were used during the Lowell work.

F) Parts and Service Calls. Based on a total item cost of \$4,722 divided equally by the 3 utilities that participated in the program for new parts, repair shop charges, and outside service calls. This item does not include MWW labor.

G) Fuel Oil. Based on an average of \$0.304/liter (\$1.15/gallon) of fuel oil and consumption of 42.4 liters/hr (11.2 gallons/hr) of reactivation or 6,959 Joules/gram (2,994 BTU/lb) of carbon.

H) Electrical Power. Based on an average cost of 7.10¢/KWH and a consumption of 48.6 KW/hr of operation for building and process energy, or 0.205 KWH/kg (0.093 KWH/lb) of GAC.

I) Water. Based on a water production cost of \$0.160/m^3 (\$0.606/1,000 gals) and a consumption of 44.64 m^3/hr (11,792 gals/hr) of reactivator operation, or 0.189 m^3/kg (22.7 gals/lb) of GAC. Approximately 92% of the water was used for reactivation and 8% used for on-site transport.

TABLE A-12 (Cont'd)

J) Lab Supplies. Based on a total item cost of $300., divided equally by the 3 utilities that participated in the program for supplies to perform reactivation process quality control analysis.

K) Depreciation. Based on the straight line depreciation calculations shown in Table 7.

L) Overhead. Based on a MWW overhead factor of 77% above labor costs that includes holidays, sick leave and fringe benefits. The total overhead for the overall MWW system is 305% and includes acquistion, treatment, distribution, and support services.

TABLE A-13. MANCHESTER WATER WORKS REACTIVATION UNIT COSTS FOR THE LOWELL, MASSACHUSETTS CARBON

	Cost Item	Cost Per Kg	(Cost Per Lb)
A)	Makeup Carbon	38.44¢	(17.44¢)
B)	Labor for Reactivation	10.23	(4.64)
C)	Labor for Transportation	2.84	(1.29)
C1)	Equipment for Transportation	6.83	(3.10)
D)	Labor for Lab	0.53	(0.24)
E)	Labor for Administration	4.37	(1.98)
F)	Parts and Service Calls	8.22	(3.73)
G)	Fuel Oil	5.34	(2.42)
H)	Electrical Power	2.49	(1.13)
I)	Water	2.89	(1.31)
J)	Lab Supplies	0.53	(0.24)
K)	Depreciation	2.54	(1.15)
L)	Overhead	13.84	(6.28)
	TOTAL COST	99.09¢	(44.95¢)

NOTE: December 9, 1981 to December 16, 1981
Based on Reactivation of 19,125 kgs (42,163 lbs) of GAC

TABLE A-14. PARAMETERS USED IN COMPUTING COST ESTIMATES FOR VARIOUS TYPES OF GAC SYSTEMS

Parameter	Value
GAC cost	\$.90/lb @ 10,000,000 lbs
O&M labor rate	\$9/hour
Electric power	\$.07/kwh
Fuel oil	\$1.20/gal
Natural gas	\$.0035/ft^3
Process and transport water	\$.50/1000 gal
Capital recovery interest	10%
Amortization period	15 years
Labor overhead	75%
Construction cost index for 1984	4131
Producers price index for 1984	302
GAC density	30 lbs/ft^3
Reactivation up-time factor	70%
Multihearth loading rate	50 lbs/ft^2/day
GAC loss, reactivation and on-site transport	15%
GAC loss, off-site transport plus reactivation	18%
Capital overhead with engineering fee	13.5%

TABLE A-15. DESIGN PARAMETERS FOR STEEL PRESSURE CONTACTOR SYSTEMS SCENARIO

	Plant Capacity (mgd)							
	1	3	5	10	25	50	100	175
Number of contactors	2	3	5	10	10	19	37	65
Hydraulic loading (gpm/ft^2)	5.46	6.14	6.14	6.14	5.52	5.82	5.97	5.95
Diameter (ft)	9	12	12	12	20	20	20	20
Area of each (ft^2)	63.62	113.10	113.10	113.10	314.16	314.16	314.16	314.16
GAC depth (ft)	10.95	12.31	12.31	12.31	11.07	11.67	11.97	11.93
Volume of GAC (ft^3) per contactor	696.64	1,392.26	1,392.26	1,392.26	3,477.75	3,666.25	3,760.50	3,747.93
EBCT (minutes)	15	15	15	15	15	15	15	15
Total Carbon loss (%)	15	15	15	15	15	15	15	15
Reactivation Frequency (no./yr)	4	4	4	4	4	4	4	4
Reactivation Demand (lbs/yr)	167,194	501,214	835,356	1,670,712	4,173,300	8,359,050	16,696,620	29,233,854
Size of each furnace (lbs/day)	-	1,962	3,270	6,539	16,335	32,716	32,674	38,139
Number of furnaces	0	1	1	1	1	1	2	3
Virgin storage size (lbs)	-	2,000	3,500	6,500	16,000	33,000	66,000	120,000

TABLE A-16. DESIGN PARAMETERS FOR CONCRETE GRAVITY SYSTEMS SCENARIO

Item	Plant Capacity (mgd)							
	1	3	5	10	25	50	100	175
Number of contactors	1	1	1	2	2	3	6	10
Hydraulic-loading (gpm/ft^2)	5.46	6.14	6.14	6.14	5.52	5.82	5.97	5.95
Area per contactor (ft^2)	127.2	339.3	565.5	565.5	1,570.8	1,989.7	1,937.3	2,042.0
GAC depth (ft)	10.95	12.31	12.31	12.31	11.07	11.67	11.97	11.93
Volume of GAC per contactor (ft^3)	1,392.84	4,176.8	6,961.3	6,961.3	17,388.76	23,219.8	23,189.5	24,361.1
EBCT (minutes)	15	15	15	15	15	15	15	15

NOTE: Reactivation requirements same as pressure contactors.

TABLE A-17. STEEL PRESSURE CONTACTOR COSTS

Item	SYSTEM (MGD) COST ($/year)							
	1	3	5	10	25	50	100	175
Process and building electric	15,823	26,740	38,136	67,206	163,926	318,464	635,299	1,129,699
Maintenance material	2,709	4,762	6,988	12,699	33,705	62,185	118,060	203,229
Labor O&M	22,160	25,970	29,255	36,116	54,611	76,984	116,147	170,048
Labor overhead	17,073	20,774	24,101	31,406	51,749	79,349	130,275	203,113
Labor for GAC transfer	576	1,728	2,879	5,759	14,385	28,814	57,553	100,769
Transfer water	167	501	835	1,671	4,173	8,359	16,697	29,234
Amortized capital	69,996	136,753	221,869	434,716	767,269	1,492,456	2,931,487	5,107,218
TOTAL COST	128,484	217,228	324,064	589,573	1,089,816	2,066,610	4,005,517	6,943,309

TABLE A-18. CONCRETE GRAVITY CONTACTOR COSTS

Item	SYSTEM (MGD) COST ($/year)							
	1	3	5	10	25	50	100	175
Process and building electric	2,903	6,012	9,138	16,549	40,939	73,019	133,687	223,313
Maintenance material	1,166	2,242	3,202	5,252	11,043	17,700	28,958	43,952
Labor O&M	8,006	10,170	12,234	16,900	31,240	49,000	80,936	125,970
Labor overhead	6,437	8,924	11,335	16,994	34,219	58,360	103,867	170,054
Labor for GAC transfer	576	1,728	2,879	5,759	14,385	28,814	57,553	100,769
Transfer water	167	501	835	1,671	4,173	8,359	16,697	29,234
Amortized capital	57,979	93,900	120,418	234,872	384,470	674,151	1,319,764	2,233,059
TOTAL COST	77,235	123,477	160,042	297,996	520,469	909,403	1,741,460	2,926,350

TABLE A-19. ON-SITE FLUID BED REACTIVATION COSTS

Item	SYSTEM (MGD) COST ($/year)						
	3	5	10	25	50	100	175
Process and building electric	4,210	7,017	14,034	35,056	70,216	140,252	245,564
Maintenance material	13,579	14,749	16,719	20,176	23,656	47,297	73,637
Labor O&M	71,986	84,079	105,643	146,649	191,218	382,244	609,241
Labor overhead	53,990	63,059	79,232	109,987	143,414	286,683	456,931
Process fuel	13,849	22,724	45,021	112,267	225,441	450,301	789,601
Process water	5,263	8,771	17,542	43,820	87,770	175,315	306,955
Makeup GAC	93,899	151,233	288,740	678,339	1,296,915	2,473,156	4,170,717
Amortized capital	172,503	184,837	207,414	251,947	302,058	603,897	946,913
TOTAL COST	429,279	536,469	774,344	1,398,240	2,340,688	4,559,144	7,599,020

TABLE A-20. ON-SITE INFRARED REACTIVATION COSTS

Item	SYSTEM (MGD) COST ($/year)						
	3	5	10	25	50	100	175
Process and building electric	30,406	48,816	94,424	229,437	452,830	904,519	1,579,164
Maintenance materials	9,174	11,236	14,797	21,282	28,039	56,051	89,400
Labor O&M	70,111	90,811	134,944	241,663	387,637	774,582	1,293,961
Labor overhead	52,583	68,108	101,208	181,247	290,727	508,936	970,470
Process water	5,263	8,771	17,542	43,820	87,770	175,315	306,955
Makeup GAC	93,899	151,233	288,740	678,339	1,296,915	2,473,156	4,170,717
Amortized capital	60,704	68,423	86,930	139,375	222,640	444,863	748,494
TOTAL COST	322,139	447,398	738,585	1,535,163	2,766,559	5,409,421	9,159,162

TABLE A-21. ON-SITE MULTIHEARTH REACTIVATION COSTS

Item	SYSTEM (MGD) COST ($/year)						
	3	5	10	25	50	100	175
Process and building electric	30,846	34,075	41,004	57,896	81,192	162,273	264,578
Maintenance materials	3,901	4,788	6,322	9,127	12,059	24,106	38,472
Labor O&M	73,920	98,706	151,096	276,327	445,753	890,708	1,488,526
Labor overhead	55,440	74,029	113,322	207,245	334,315	668,031	1,116,394
Process fuel	49,304	76,750	141,209	318,748	593,270	1,185,175	2,041,951
Process water	5,263	8,881	17,542	43,820	87,770	175,315	306,955
Makeup GAC	93,899	151,233	288,740	678,339	1,296,915	2,473,156	4,170,717
Amortized capital	148,153	231,286	257,386	322,051	412,527	824,621	1,319,748
TOTAL COST	460,726	679,638	1,016,623	1,913,553	3,263,801	6,403,384	10,747,342

TABLE A-22. COST ITEMS INCLUDED IN THE GAC TREATMENT PROCESSES

GAC CONTACTORS

Capital

(a) construction cost of contactor system

(b) virgin GAC storage cost

(c) process pumping cost (for pressure contactors)

(d) capital overhead cost plus engineering fee

(e) initial GAC cost

O&M

(a) contactor process electric cost

(b) contactor O&M labor cost

(c) contactor maintenance materials cost

(d) process pumping electric cost (pressure contactors)

(e) process pumping labor cost (pressure contactors)

(f) process pumping maintenance materials cost (pressure contactors)

(g) labor cost for on-site GAC transport

(h) water cost for on-site GAC transport

(i) overhead cost on all labor

TABLE A-22. (Cont'd)

REACTIVATION

Capital

(a) construction cost of reactivation system

(b) capital overhead cost plus engineering fee

O&M

(a) process electrical cost

(b) building electrical cost

(c) maintenance materials cost

(d) reactivator O&M labor cost

(e) process fuel cost

(f) GAC makeup cost

(g) process water cost

(h) overhead cost on all labor

OFF-SITE GAC TRANSPORT

Capital

(a) cost of transport vehicles

O&M

(a) transport labor cost (loading, haul, and off-loading)

(b) transport fuel cost

(c) maintenance materials cost for vehicles

TABLE A-23. COST ESTIMATING FUNCTIONS

Capital Cost Equation Form

$CC = [a+b(USRT)^{c}](NU)(CCI/2850.7) + (OHEF)$

$AC = (CC)\ (I(1+I)^{N}/((1+I)^{N} -1))$

where

CC = construction cost, \$

AC = amortized capital cost, \$/year

a,b,c = equation coefficients and exponent

USRT = design variable

NU = number of units in process (i.e., NU = 1 for a single contactor or reactivator)

CCI = ENR construction cost index, base year 1913

OHEF = overhead, interest during construction, engineering fees, \$ (must be added separately)

I = period interest rate (decimal)

N = payback period, years

TABLE A-23. (Cont'd)

Capital Cost Function Coefficients and Exponents

Process Name	USRT Range	a	b	c
Steel Pressure Contactors[1]	390-2,260 ft^3	80475	106.67	0.919
Concrete Gravity Contactors[1]	350-10,600 ft^3	0	16418.64	0.359
In-Plant Pumping[2]	1-10 mgd	25429	2531.07	1.334
	10-200 mgd	50163	2390.25	1.134
On-site GAC Storage[3]	1,000-20,000 ft^3	14106	6.69	1.098
Cost of GAC[4]	10,000-10,000,000 lbs	0	?	0.933
Fluid Bed Reactivation[5]	6,000-50,000 lbs/day	599030	4694.80	0.494
Infrared Reactivation[5]	2,400-50,000 lbs/day	222261	49.52	0.933
Multihearth Reactivation[6]	27-47 ft^2	521081	3.13E-6	6.726
	47-1,510 ft^2	898670	6806.69	0.771

TABLE A-23. (Cont'd)

O&M Cost Equation Forms

$PE = [d+e(USRT)^{f}](NU)(\$/kwh)$

$PE = [d+e(USRT)^{f}](TDH/35)(NU)(\$/kwh)$ for in-plant pumping

$BE = [g+h(USRT)^{i}](NU)(\$/kwh)$

$MAINT = [j+k(USRT)^{\ell}](PPI/199.7)(NU)$

$MAINT = [j+k(USRT)^{\ell}(MILES)^{\ell\ell}](PPI/199.7)$ for off-site GAC transport

$LABOR = [m+n(USRT)^{o}](NU)(\$/hour)$

$LABOR = [m+n(USRT)^{o}(MILES)^{oo}](\$/hour)$ for off-site GAC transport

$FUEL = [p+q(USRT)^{r}](NU)(\$/ft^{3})$ for natural gas

$FUEL = [p+q(USRT)^{r}](1/139)(NU)(\$/gallon)$ for fuel oil

$FUEL = [p+q(USRT)^{r}(MILES)^{rr}](\$/gallon)$ for off-site transport

Where: all O&M costs are in \$/year and assume utilization 100% of the time. Therefore, adjust cost estimates according to the percent utilization.

PE = process electrical cost

BE = building electrical cost

MAINT = maintenance materials cost

LABOR = process O&M labor cost

FUEL = process natural gas cost, process fuel oil cost, or transport diesel cost

d,e,f,...q,r,rr = equation coefficients and exponents

USRT = design variable

MILES = one-way distance in miles

TDH = total dynamic head (feet)

NU = number of units in process. This variable is applicable only to in-plant pumping, multihearth reactivation, infrared reactivation, and fluid bed reactivation. NU = 1 for the other processes, i.e., contactors and off-site transport.

PPI = producers price index value

TABLE A-23. (Cont'd)

O&M Cost Function Coefficients and Exponents

Process Name	USRT Range	Model Values
Steel Pressure Contactors[7]	157-6,790 ft^2	d=0; e=5.92; f=0.999; g=146831; h=130.19; i=1.093; j=774; k=5.07; ℓ =1.007; m=1572; n=12.57; o=0.698
Concrete Gravity Contactors[7]	140-28,000 ft^2	d=9; e=4.83; f=1.000; g=10831; h=361.31; i=0.912; j=109; k=17.99; ℓ =0.744; m=701; n=3.25; o=0.838
In-plant Pumping[2]	1-10 mgd	d=0; e=52467.0; f=0.999; j=263; k=86.71; ℓ =1.188; m=476; n=44.13; o=0.777
In-plant Pumping[2]	10-200 mgd	d=0; e=52465.0; f=1.000; j=0; k=341.54; ℓ =0.812; m=574; n=12.60; o=1.112
Off-site GAC Transport[8] (< 25 miles)	30,000-3,000,000 lbs	j=0; k=2.31E-5; ℓ =0.992; ℓℓ =1.015; m=2.5; n=3.15E-5; o=1.067; oo=0.477; p=0; q=2.38E-5; r=0.989; rr=0.984
Off-site GAC Transport[8] (> 25 miles)	30,000-3,000,000 lbs	j=0; k=2.16E-5; ℓ =1.001; ℓℓ =0.998; m=0; n=1.91E-4; o=1.021; oo=0.131; p=0; q=1.83E-5; r=1.000; rr=1.012
Fluid Bed Reactivation[5]	6,000-50,000 lbs/day	d=0; e=43.80; f=1.000; j=7232; k=385.19; ℓ =0.353; m=4000; n=245.0; o=0.450; p=111107; q=1046.14; r=1.008
Infrared Reactivation[5]	2,400-60,000 lbs/day	d=44779; e=315.55; f=0.988; g=417; h=23.14; i=0.753; j=0; k=427.25; ℓ =0.397; m=4000; n=25.7; o=0.742
Multihearth Reactivation[6]	27-1,510 ft^2	d=472706; e=8517.36; f=0.755; g=11246; h=312.08; i=0.649; j=0; k=846.15; ℓ =0.401; m=3000; n=604.0; o=0.728; p=366525; q=287714.93; r=0.899

TABLE A-24. ASSUMPTIONS USED IN COST ANALYSIS

Footnotes for Processes

1. Capital cost based on effective GAC volume (ft^3) of an individual contactor.

2. Pump cost based on the capacity of an individual pump (mgd); capital cost includes a standby pump.

3. Cost based on total storage volume (ft^3); NU = 1.

4. Given the cost of GAC ($) for a specified amount (pounds), calculate coefficient "b". The equation cost = b(pounds)$^{.933}$ can then be used to estimate cost of GAC for different amounts. For example, in this report $0.90/pound GAC cost at 10,000,000 pounds was assumed; therefore "b" is 2.65; GAC cost ($) = 2.65(pounds GAC)$^{.933}$. NOTE: NU = 1.

5. Costs based on pounds per day capacity of a single reactivator. O&M costs assume 100% utilization, adjust estimates according to estimated usage.

6. Costs based on effective hearth area of (ft^2) of a single reactivator. O&M costs assume 100% utilization, adjust estimates according to usage.

7. O&M cost based on total filter surface area of all contactors combined.

8. Off-site GAC transport cost, O&M only (capital must be added separately); cost based on pounds of dry GAC hauled. If GAC is wet-drained and road weight limits exist then the number of truck-loads may double; thus double the estimates.

9. Overhead cost on capital is 13.5% of total construction expense.

10. Labor for on-site GAC transport is 0.383 manhours/1000 pounds of GAC transferred

11. Water for on-site GAC transport is 2 gallons per pound of GAC transferred.

12. Water for reactivation process is 21 gallons per pound of GAC required to be reactivated.

13. TDH = 35 (feet) for pressure contactors

14. Off-site transport O&M costs (labor, materials, and fuel) were doubled, assuming wet-drained GAC was being hauled and road weight limits existed; sum of transport LABOR, MAINT, and FUEL was multipled by 2.

15. Transport vehicles cost $75,000 each.

EXHIBIT 1

COST FUNCTION DEVELOPMENT

The cost estimating equations presented in Table A-22 were developed in a three step process. The first step involved developing initial mathematical functions for the basic cost components of each treatment process (i.e., for a fluid bed reactivator, the major cost components include capital, labor, electrical, fuel, and maintenance materials). The mathematical equations were developed using a nonlinear function form of $COST = a + bX^c Y^d$.... where X and Y are independant design variables and a,b,c,d are coefficients and exponents determined from nonlinear regression analysis. The design and cost data used to derive the intial equations were obtained from a previous EPA cost estimating study (Culp/Wesner/Culp).(36)

The second step in the development of the equations was to compare cost estimates computed from the initial functions with actual cost data obtained from several operating systems. Cost comparisons were made using data obtained from Cincinnati Water Works, Manchester Water Works, Passaic Valley and Water Factory #21. The third step in the equation development process was to make necessary modifications to the initial cost equations as determined from the comparison of estimates with actual data.

Based on comparisons of cost data obtained from actual operating experience and estimates generated from the equations, most of the cost functions did not require major modifications. The cost equations that required some modification were:

a) capital cost for steel and concrete GAC contactors;

b) process electrical energy for fluid bed and multihearth reactivation;

c) O&M labor for fluid bed, infrared, and multihearth reactivation.

The capital cost estimates associated with GAC contactors were low compared to actual construction data. All of the construction-related elements included in the actual operating system did not appear to be included in the derivation of the original cost estimates from which the equations were based. Therefore, the steel and concrete GAC contactor capital cost functions were adjusted by an appropriate factor, in order to account for the differences.

The process electrical energy estimates associated with fluid bed and multihearth reactivation were lower than actual experience. This was partly because the estimates did not include consumption of electrical energy during reactivator start-up and shut-down. Also, building-related electrical energy was not taken into account for fluid bed reactivation. Therefore, these equations were also adjusted by an appropriate factor.

The reactivation O&M labor estimates were extremely low (i.e., a factor of 10) compared to actual full-scale reactivation experience. The original labor estimating data from which the initial equations were based were primarily obtained from manufacturers' estimates of reactivation requirements. Actual experience showed that even though the equipment was automated an operator was required continuously while the reactivtor was in operation. The O&M reactivation labor functions were redeveloped based on actual operating experience. The new labor functions were developed on the premise that there would be a minimum number of manhours required to operate a reactivator regardless of it's size and additional operation and maintenance manhours required exhibiting economies of scale. If multiple furnaces were operated at a plant then an additional operator would be required for each furnace. Therefore, no economies of scale were assumed to exist with respect to the number of furnaces at a plant. The CWW and MWW reactivation labor data were used to calibrate the new functions, and the Culp/Wesner/Culp data were used to determine the appropriate economies of scale factors.

TABLE A-25. RESULTANT REGRESSION EQUATIONS FOR MODEL FUNCTION PARAMETERS

$$\begin{aligned} C = {} & \mathrm{PDRATIO}\cdot(0.07368) + \mathrm{EBCT}\cdot(0.002377\ \mathrm{min}^{-1}) + \mathrm{MOLASS}\cdot(0.001804\ \mathrm{DI}^{-1}) \\ & + \mathrm{MESHSIZE}\cdot(0.0001838\ \mathrm{mm}^{-2}) - \mathrm{IODIN}(0.00001932\ \mathrm{g}\cdot\mathrm{mg}^{-1}) \\ & - 0.1445\ \mathrm{mg}\cdot\mathrm{kg}^{-1} \end{aligned}$$

where: PDRATIO = unitless ratio described in text
EBCT = empty bed contact time in minutes
MOLASS = molasses # in DI/g
MESHSIZE = product of screen dimensions described in text
IODINE = iodine # in mg/g

$$R = \mathrm{APS\_TOC}\ (109.3\ \mathrm{mg}^{-1}\cdot\mathrm{liter})$$

Note: As described earlier, APS_TOC is the slope of the 'best-fit' line describing the plot of TOC applied to the GAC in mg/liter vs runtime in days. The rate of applied TOC is presumed to be relatively constant over time. This assumption was valid in all 15 model cases.

$$K = R\cdot(35.95\ \mathrm{days}) + \mathrm{DEPTH}\cdot(0.02778\ \mathrm{in}^{-1}) + 3.293$$

where: R is determined above
DEPTH = depth of GAC in inches.

TABLE A-26. MODEL STUDY CASE DESCRIPTIONS

Case 1: Cincinnati Water Works, filter adsorber 15A, project phase 3-0, 181 run days from 1/14/80 through 7/14/80, Westvaco WVG 12x40 virgin GAC.

Case 2: Cincinnati Water Works, filter adsorber 15A, project phase 3-1, 46 run days from 8/11/80 through 9/26/80, Westvaco WVG 12x40 once reactivated GAC.

Case 3: Cincinnati Water Works, filter adsorber 15A, project phase 3-2, 44 run days from 10/20/80 through 12/2/80, Westvaco WVG 12x40 twice reactivated GAC.

Case 4: Cincinnati Water Works, filter adsorber 15A, project phase 3-3, 64 run days from 12/22/80 through 2/24/81, Westvaco WVG 12x40 thrice reactivated GAC.

Case 5: Cincinnati Water Works, full scale contactor D, project phase 3-0, 206 run days from 1/14/80 through 8/7/80, Westvaco WVG 12x40 virgin GAC.

Case 6: Cincinnati Water Works, full scale contactor D, project phase 3-1, 106 run days from 9/1/80 through 12/16/80, Westvaco WVG 12x40 once reactivated GAC.

Case 7: Evansville Water Works, full scale contactor T4P, project phase 6, 85 run days from 9/18/79 through 12/11/79, ICI Hydrodarco 10x30 virgin GAC.

Case 8: Evansville Water Works, full scale contactor T5P, project phase 6, 85 run days from 9/18/79 through 12/11/79, ICI Hydrodarco 10x30 once reactivated GAC.

Case 9: Evansville Water Works, full scale contactor T4P, project phase 7, 84 run days from 3/4/80 through 5/27/80, ICI Hydrodarco 10x30 virgin GAC.

Case 10: Evansville Water Works, full scale contactor T5P, project phase 7, 84 run days from 3/4/80 through 5/27/80, ICI Hydrodarco 10x30 twice reactivated GAC.

Case 11: Evansville Water Works, full scale contactor T4P, project phase 8, 81 run days from 9/9/80 through 1/13/81, ICI Hydrodarco 10x30 thrice reactivated GAC.

TABLE A-26 (cont). MODEL STUDY CASE DESCRIPTIONS

Case 12: Manchester Water Works, full scale GAC filter, project phase 1, 127 run days from 1/31/80 through 5/30/80, Westvaco WVW 8x30 virgin GAC.

Case 13: Same as case 12 with once reactivated GAC.

Case 14: Manchester Water Works, full scale GAC filter, project phase 2, 110 run days from 8/28/80 through 12/19/80, Westvaco WVW 8x30 twice reactivated GAC.

Case 15: Manchester Water Works, full scale GAC filter, project phase 3, 88 rundays from 2/16/81 through 5/17/81, Westvaco WVW 8x30 thrice reactivated GAC.

TABLE A-27. TOC PILOT STUDY CASE DESCRIPTIONS

Case 1: Cincinnati Water Works, filter adsorber 15A and pilot column RV5, project phase 3-0, 181 run days from 1/14/80 through 7/14/80, Westvaco WVG 12x40 virgin GAC.

Case 2: Cincinnati Water Works, filter adsorber 15A and pilot column RV3, project phase 3-1, 46 run days from 8/11/80 through 9/26/80, Westvaco WVG 12x40 once reactivated GAC.

Case 3: Cincinnati Water Works, filter adsorber 15A and pilot column RV3, project phase 3-2, 44 run days from 10/20/80 through 12/2/80, Westvaco WVG 12x40 twice reactivated GAC.

Case 4: Cincinnati Water Works, filter adsorber 15A and pilot column RV3, project phase 3-3, 64 run days from 12/22/80 through 2/24/81, Westvaco WVG 12x40 thrice reactivated GAC.

Case 5: Cincinnati Water Works, full scale contactor D and pilot column PFA5, project phase 3-0, 206 run days from 1/14/80 through 8/7/80, Westvaco WVG 12x40 virgin GAC.

Case 6: Cincinnati Water Works, full scale contactor D and pilot column PFA5, project phase 3-1, 106 run days from 9/1/80 through 12/16/80, Westvaco WVG 12x40 once reactivated GAC.

Case 7: Cincinnati Water Works, full scale contactor D and pilot column PFA5, project phase 3-2, 128 run days from 12/29/80 through 5/6/81, Westvaco WVG 12x40 twice reactivated GAC.